OUTLINE OF RADIO

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PREFACE

THE object of the present book is to provide a readable and up-to-date outline of the principles upon which the whole science of Radio is based; to show how the necessary components of a radio circuit are designed to fulfil the theoretical requirements; and to deal with radio-frequency amplification, detection, the principles of superheterodyne receivers, automatic volume control, low-frequency amplification, and the output stage.

The special technique which is necessary when working with short and ultra-short waves is fully described, as are also television, radio direction finding, and radar.

In order to ensure the best possible treatment for each section of the subject the services of specialist contributors have been enlisted.

Dr. M. G. Say, is the Professor of Electrical Engineering at the Heriot-Watt College, Edinburgh.

Mr. R. S. Elven is a practising Radio Engineer, who has made a special study of short wave and ultra-short wave technique.

Although radar has been developed to a high state of perfection and requires very considerable scientific knowledge for its complete understanding, it will be found that Mr. H. E. Penrose, late of the Admiralty Signal Establishment, has succeeded in presenting an outline of the subject which can be understood by any reader after he has grasped the simple principles outlined in the earlier chapters of the book.

Mr. T. J. Fielding, a chartered electrical engineer, is author of textbooks on electrical engineering subjects, having made a particular study of photo-electric cells and cathode-ray tubes.

Mr. R. C. Walker, another well-known writer on electrical subjects, is employed by one of the largest manufacturers of

radio and television receivers. Mr. Walker has kept in close touch with developments in this field.

The late Mr. G. Windred was a consulting electrical engineer with a particular knowledge of the Theory and Design of Electro-magnetic Appliances.

Mr. C. A. Quarrington has been closely associated with the development of valves, cathode-ray tubes and their application in modern television receivers.

No attempt has been made to describe the detailed construction of radio receivers, but in Chapter XX some typical receiver circuits are set out and explained in detail, so that the radio service man and amateur should be able, after studying these, to find his way about any particular type of receiver with which he may have to deal.

E. M.

CONTENTS

PAGE

CHAPTER I. WHAT IS ELECTRICITY? - - - - - 9

Fundamental Ideas — Molecules — Atoms — Electrons — Electrification, or Charging—Conduction—Forms of Current—Electrical Effects.

CHAPTER II. HOW ELECTRICAL ENERGY IS PRODUCED - 33

Atomic Energy—The Chemical Production of Electricity, Primary Cells—The Electromagnetic Production of Electricity—Thermo-electric Effects—Piezo-electricity—The Production of Electron Currents.

CHAPTER III. HOW ELECTRICAL ENERGY IS USED - - 57

Electrical Heating—Valve Cathodes—Resistance Welding—Arc Welding—Arc Furnaces—Eddy Current Heating—Capacity Current (Dielectric) Heating—Electric Lighting—Electric Power—D.C. Motors—A.C. Motors—Convertors — Boosters — Transformers — Auto-transformers — Rectifiers — Electrochemistry.

CHAPTER IV. HOW ELECTRICAL QUANTITIES ARE MEASURED 101

Classification—Damping—Ammeters and Voltmeters—Wattmeters—Supply Meters—Electromagnetic Instruments—Thermal Type Meters—Electrostatic Voltmeters—Radio Applications of Voltmeters and Milliammeters.

CHAPTER V. RADIO WAVES AND BROADCASTING - - 123

Radio Frequencies—Wireless Waves—Wavelength—Velocity of the Waves—Converting Wavelength into Frequency—The Propagation of Radio Waves—How Radio is Broadcast—Amplitude Modulation—Frequency Modulation—Broadcast Relay Systems.

CHAPTER VI. RESISTANCES AND POTENTIOMETERS - - 147

Charts and Graphs—Voltage Drop Calculations—Power Rating—Series and Parallel Connections—Series Parallel Connections—Applications of Resistances—Potentiometers—How to Choose Resistances and Potentiometers for Wireless Circuits.

CHAPTER VII. CHOKES - - - - - - - - - 175

Radio-frequency Chokes—Forms of Construction—The Magnetic Properties of Iron—Low-frequency and Smoothing Chokes.

CHAPTER VIII. TRANSFORMERS - - - - - - 199

Input and Output Circuits—Power Factor—Input Losses—Turns Ratio—Mutual Induction—Input Impedance—Frequency and Amplitude Distortion—Amplification Curves—Applications of Audio-frequency Transformers.

CHAPTER IX. CONDENSERS AND CAPACITY - - - 215

Types of Condensers—Comparison of the Main Types—How to Determine the Capacity—Design of Variable Condensers—Fixed Condensers.

CHAPTER X. INDUCTANCE AND TUNING - - - - - 229

Calculating Inductance—Induction in Wireless Circuits—Mutual Inductance—Tuned Circuit Calculations—Steinmetz's Law—The Impedance of a Circuit—Tuned Circuits—Equal Negative and Positive Reactances—Resonant Frequency—Impedance at Various Frequencies—Effect of Resonance on a Parallel Circuit—Magnification Factor—Tuning Coils.

CHAPTER XI. VALVES - - - - - - - - - 257

Electron Emission—The Diode—The Triode—The Tetrode—The Pentode—The Radio Frequency Amplifier—Tuned Grid Coupling—The Tuned Transformer—The Variable-mu Characteristic—The Frequency Changer—The Triode Hexode—The Pentagrid—The Triode Pentode—Detection—The Anode Bend Detector—The Diode Detector—The Leaky Grid Detector—Infinite Impedance Detection—Reaction—Automatic Volume Control—The Valve as Audio-frequency Amplifier—The Power Output Tetrode and Pentode—Negative Feedback—Multi-assembly Output Valves—The Valve as a Rectifier—The Mercury Vapour Rectifier—The Ionic-heated Cathode Rectifier Valve—The Gas-discharge Triode—Transmitting Valves—A General Survey.

CHAPTER XII. RADIO-FREQUENCY AMPLIFICATION - - 329

Function of the Radio-frequency Valve—Anode Current Variations—Types of Radio-frequency Circuit—Degree of Amplification—Selectivity—Quality of Reproduction—Practical Radio-frequency Valve Stages.

CONTENTS

PAGE

CHAPTER XIII. THE DETECTOR STAGE - - - - 341

Frequency Separation—Feedback—Diode Detectors—Triode Detectors—Grid Detection—Component Valves—Power Grid Detection.

CHAPTER XIV. THE SUPERHETERODYNE RECEIVER - - 353

General Principles—Beat Frequencies—Supersonic Frequencies—Selectivity—Second Channel Interference—Frequency Conversion—Radio-frequency Amplification—Beat Interference—Harmonics—Side Bands—Oscillator Drift—Tuning Indicators—Automatic Tuning Devices.

CHAPTER XV. AUTOMATIC VOLUME CONTROL - - - 377

Varying the Receiver Amplification—The Variable-mu Valve—Delayed A.V.C.—Modifications—Amplified A.V.C.—Noise Suppression.

CHAPTER XVI. LOW-FREQUENCY AMPLIFICATION - - 385

Principles—Resistance Capacity Coupling—Transformer Coupling—Conditions for Good Reproduction—Push-pull Amplification—Cathode Follower Circuits—Volume Compression and Expansion.

CHAPTER XVII. LOUDSPEAKERS, MICROPHONES AND PICK-UPS 411

Moving Coil Speakers—Public Address Equipment—Extension Speakers—Microphones—Microphone Leads—Pick-ups.

CHAPTER XVIII. POWER SUPPLY FOR RADIO SETS - - 437

Batteries—Mains Supply—A.C. Receivers—Rectifiers—Mains Transformers—Cathode Heater Circuits—A.C./D.C. Receivers—Barretters—Eliminators—Vibrators—Rotary Transformers—Motor Generators—Interference Suppression.

CHAPTER XIX. ACCUMULATORS - - - - - - 463

Lead-acid Cells—Alkaline Cells—The Care and Maintenance of Accumulators.

CHAPTER XX. RADIO RECEIVER CIRCUITS EXPLAINED - 477

Accessories—Straight Three Valve Receiver—Portable Superheterodyne Receiver—8-Valve Superheterodyne Receiver—Car Radio—Television Receiver.

CHAPTER XXI. SHORT WAVE AND ULTRA-SHORT WAVE TECHNIQUES - - - - - - - - - - 495

Wavelengths—Transmission of Short Waves—Reflectors—Aerial Arrays—Reception of Short Waves—Matching—Receiver Design.

CHAPTER XXII. THE CATHODE-RAY TUBE - - - - 517

Principles of Operation—Time Base Circuits—Gas-filled Relays—Fluorescent Screen Materials—Double Beam C.R. Tubes—High Voltage Tubes—Power Supplies.

CHAPTER XXIII. PHOTO-ELECTRIC CELLS - - - 535

Photo-electricity—Types of Cell—Photo-conductivity—Photovoltaic Effects—The Becquerel Effect.

CHAPTER XXIV. PRINCIPLES OF TELEVISION - - - 551

The Transmitter—Television Receiver—Cathode-ray Tube—Scanning—Vision Channel—Time Base—Synchronisation and Linearity—The Complete Receiver Circuit—Installation of the Receiver—Maintenance.

CHAPTER XXV. RADIO DIRECTION-FINDING - - - 591

Radiation—Loop Aerials—Bearings—Sense Determination—Types of Aerials—Aircraft Direction-Finding—Visual Indicators—Ground Direction-Finding Beacons—Position Finding—Pulse-modulated Systems—The Gee System—The Loran System.

CHAPTER XXVI. A SURVEY OF RADAR - - - - - 615

Classified Applications—The Use of the Cathode-ray Tube—Measurement of Bearing—Beam Widths—Beam Splitting—Basic Principles of Radar Systems—Calibration and Range Mark Generators—Major Units and Constants—Transmitters—Classification of Pulsing Systems—Transmitters—Receivers—The Resonant Magnetron—The Reflex Klystron.

INDEX - - - - - - - - - - - 679

CHAPTER I

WHAT IS ELECTRICITY?

The explosion of the first atomic bomb at Hiroshima, Japan, on August 6th, 1945, with its devastating effect, not only shook the unfortunate Japanese, but also left the rest of the world in a very uneasy frame of mind. A new force had been harnessed and exploited which might either be of great service to mankind, or eventually destroy it.

The military use of the atomic bomb, together with the experimental "Operations" which took place later at Bikini, in the Pacific, aroused the interest of people everywhere. Out of the fog of political censorship, a host of strange and unfamiliar words and phrases emerged such as "uranium," "protons," "neutrons," "splitting the atom," with vague references to "heavy water" and mysterious equipment called "the cyclotron." In fact, the subject of atomic power became the chief topic and was widely discussed in newspaper articles, on the radio, and in our homes.

Hiroshima, Bikini and the atomic bomb seem to be a far cry from the home wireless set, radar and the study of electricity, but in the following chapters you will be renewing your acquaintance with some of these words and phrases as modern ideas on the nature of electricity are closely linked with the theory of the nuclear atom, which formed a basis for the development of the atomic bomb.

In spite of all the advances made in the study and application of electricity, no satisfactory theory of electricity was forthcoming until 1911, when Rutherford advanced the theory that the whole mass of an atom was concentrated in a minute central nucleus which carried a positive electric charge.

From his experiments Rutherford deduced that an atom can

be considered as an infinitesimal solar system in which the electrons, representing the planets, revolve round the nucleus, or sun, calling to mind an ultra-microscopic model of our own solar system. The relation of this theory to electricity is shown later.

Fundamental Ideas

Electrical science and its application had made enormous strides before more than an inkling of its fundamental physical nature was realized. On a basis of pure experiment or of various "fluid" theories, generators and motors, arc- and glow-lamps, batteries, magnets and a great range of electrical devices had already been successfully developed by 1897, when the electron theory was formulated. Even the thermionic valve had appeared in an elemental form, and radio would have developed by its aid, without doubt. But the rate of progress since 1900 has been phenomenal, and this could not conceivably have occurred without the physical theory, which first followed practice to explain it, and now precedes practice—in fact, predicts it.

It is not necessary to have an electronic theory to explain quite large and important sections of electrical engineering practice—particularly in the field of electrical machines. But radio practice is very wide indeed, and makes use of the most recent developments of science; and it is consequently most desirable that at least a simplified version of the fundamental ideas underlying electrical behaviour be appreciated.

All material things—solid, liquid or gaseous—are at base electrical in essential nature. This is now universally accepted, and it leads, among other things, to a rational explanation of many electrical phenomena—although it would be desirable here to qualify the word "explanation." What is really meant is this: given a set of assumed or experimental facts, then an explanation can be given in terms of them. The facts themselves just have to be accepted. An advance in physical science means one step deeper towards even more fundamental facts. But we shall always have to say at some point or other—however far we go—that "this is so because it jolly well is so!" No "explanation" can really be more than that. Again, every new advance in theory is a further refinement. Quite an

adequate picture of many radio phenomena can be given in terms of ideas that leading scientists to-day would think quite crude. Engineers are practical people, and, burdened as they must be with the pressing business of getting the world's work done, are in the habit of choosing their fundamental ideas at a level most suitable for themselves. We shall do the same.

Electric Charge

Electricity is of commercial importance not because of what it *is*, so much as of what it can *do*. Electricity is of value because it can heat houses, light streets, drive trams and send messages. All these useful things are obtained from engineered applications of the *effects* of electricity. The effects are in turn the results of the position and movement of electric *charges*.

It is quite difficult to get first-hand knowledge of what is meant by an electric charge, because the effects easily producible are very small The quite different (though related) phenomena of magnetism are much more familiar because the effects are powerful. Everyone has experimented with bar magnets and has *felt* the peculiar forces of attraction and repulsion that are so easily observed. And to know if a piece of steel is a magnet you try it, to find out if the effects are produced. N and S marks on the ends, or paints or labels are of no significance; if the effects are not there, the thing isn't a magnet. The existence of mechanical forces of attraction and repulsion is the *only* criterion, and is in fact used to define magnetism.

In an analogous manner, pieces of matter in a certain physical state other than the magnetic can show similar mechanical forces. Vigorous use of a vulcanite comb in the hair, or rapid removal of a silk vest on a dry day, both give evidence of an "electrified" or "charged" state. A charged comb will attract and pick up small pieces of paper, and cause hairs to move in an amusing manner. Here again we have a mechanical effect in the space affected by the separation of electric charges.

Electrical phenomena can be explained in terms of charges at rest, in motion, and in acceleration. Charges at rest show the mechanical forces just described, together with the energy-storage system called the capacitor or condenser. Charges in motion have additional effects to show, as they form the familiar

electric current with, among other things, its electromagnetic phenomena. When charges are accelerated or retarded—especially suddenly—an effect fundamental to radio can take place: electromagnetic radiation of energy as waves.

Charge, then, is an important concept. A great advance was made when it was shown that electric charge is far from being an occasional or " freak " phenomenon, but is one of the basic " bricks " from which the whole material universe is built.

MOLECULES, ATOMS AND ELECTRONS

It is well known that material substances, whether solids, liquids or gases, are composed of enormous numbers of tiny mass-particles called *molecules.* If a piece of copper were sub-divided again and again (an operation not possible by any ordinary mechanical means, of course) each fragment would be recognizable as copper until divided down to the molecule, the smallest portion that can exist by itself and still show all the essential characteristics of the metal. Any further sub-division produces something new and unlike the original material.

Molecules

In all states of matter molecules are in a state of rapid continuous motion. In a solid they are closely packed (relatively, that is: the concentration would appear very sparse indeed, were it visible) and, although moving, do not leave a mean fixed position so that the molecular structure has a permanent " lattice " pattern, giving to the solid its definite shape. Elastic materials like rubber have crinkly " chains " of molecules which give " stretchability." In a liquid, the molecules have a weaker cohesion and wander about with some freedom, so that the liquid takes up the shape of the vessel in which it is contained. In a gas, the molecules are still more mobile and relatively far apart. The cohesive force is small and the gas fills its container and is easily compressed or expanded.

When substances are heated the molecular activity becomes more intense, and expansion or internal pressure result.

Molecules can be sub-divided, but the constituent particles, called *atoms,* differ from the molecules of which they form a part: just as a crowd of 100 men could be divided down into units of no less than one *man*—any further sub-division will make rather a fatal difference! An atom is the smallest particle

of matter that can be found existing stably, and it generally exists only in combination with other atoms. A molecule can consist of one (very occasionally), two or more atoms: sometimes the number runs into hundreds or thousands. A substance whose molecules consist of atoms all of the same kind is an *element*. Otherwise it is a *compound*.

There appear to be only 92 elements, from combinations of which every substance in the universe is made. The simplest element is Hydrogen: its molecule has two atoms, and in a gram of hydrogen the number of molecules is given approximately by 3×10^{23}, or 3 followed by 23 noughts.

Atoms.

Atoms have a highly characteristic structure of their own. Three kinds of particles—*electrons*, *protons* and *neutrons*—go to make up an atom, and the numbers of particles determine the kind of element. An *electron* is a minute negative electric charge of almost massless nature. A *proton* is electrically the opposite of an electron, having an equal positive charge, but it is associated with a small mass 1,800 times that of the electron. A neutron is a chargeless mass, the same as that of the proton. The total mass of any atom is sum of the proton and neutron masses in its make-up, and the mass of a molecule is that of its constituent atoms.

Atomic Structure.—The neutrons and protons of an atom are linked together to form a compact *nucleus*, while the electrons travel in orbits round the nucleus like planets round a sun. The simple hydrogen atom has a single proton as nucleus and

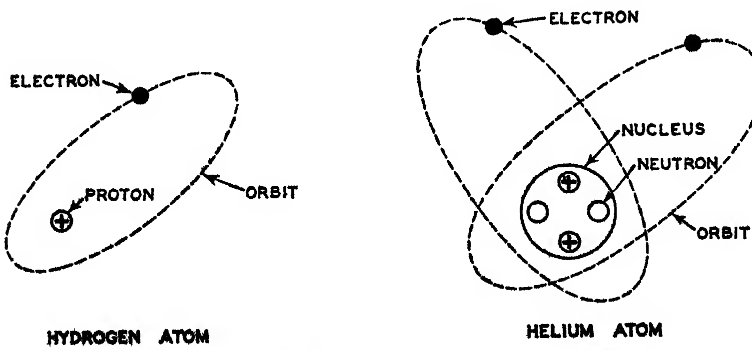


FIG. 1.—DIAGRAM (IMAGINARY) OF ATOMIC SYSTEMS.

a single electron as planet, Fig. 1. Helium has a nucleus with two protons and two neutrons, and two planetary electrons occupying different orbits spin round the nucleus. Copper is much more complicated, as it has a nucleus with 29 protons and 35 neutrons, together with a planetary cloud of 29 electrons. The *atomic weight* of an atom is the number of protons and neutrons it contains, for in these particles, which form the nucleus, the mass is concentrated. The *atomic number* is the number of electrons in the planetary system, or the number of protons in the nucleus: that is, the number of negative or positive charges. Normally these numbers are equal, and the atom is electrically balanced.

The atomic weights vary between 1 for hydrogen and 238 for uranium, and the range of atomic numbers is from 1 to 92.

Electrons

It would be quite logical with our present advanced physical knowledge to use the electron's own charge as the fundamental unit and to count all other charges in terms of the electrons contained in them. In fact, however, a unit of charge has long since been decided upon: this is the *coulomb*, equivalent to $6{\cdot}2 \times 10^{18}$ electron charges. The electron charge is $1{\cdot}6 \times 10^{-19}$ coulomb.

The electrons in the planetary system of an atom have definite orbital groups, called shells. The innermost group holds one or two electrons. If the atom has more than two, the remainder will be found in a second group, outside the first and holding up to 8, a third holding up to 18, and so on. The chemical nature depends considerably on how nearly full the outermost shell is.

Remembering that, in a normal atom, the positive charge of all the protons in the nucleus just balances the negative charges of the orbital electrons, the atom is seen to be electrically neutral. There will be forces of attraction between nucleus and "planets," which keep the atom together. The electrons do not collapse into the nucleus for the same reason that the earth does not fall into the sun: there is an orbital spin, and electrons travel at tremendous speed round and round their nucleus.

Electrons of the outer orbital shell, by reason of all the negative charges on the other inner shells between them and the nucleus, will be most loosely attached to their atoms, and

they can in fact be sometimes removed and either liberated or attached to other atoms in the same mass. As soon as an atom loses an electron, its charge-balance is disturbed, its nuclear positive charge preponderates, and the atom acts externally as if it had a positive charge. If an atom gains an electron into its outer shell it acquires an unbalanced negative charge. This process is called *ionization*. Ionized atoms, called *ions*, become subject to the influence of externally-applied electrical control.

Ionization in gases may occur due to irradiation by light, especially ultra-violet light. This takes place, for instance in the ionosphere, many score miles above the surface of the earth, due to the effect of the sun, and the ionization profoundly influences short-wave radio propagation. Gaseous ionization may also occur if fast-moving free electrons are shot through the gas: collisions occur between free electrons and the gas molecules, with the result that outer-shell electrons are torn off them. This phenomenon is found in gas-filled valves. Surface ionization of a material can be developed by rubbing it (the classic catskin and glass-rod, or the fountain-pen and sleeve experiments fall into this class), by illuminating it (as in the photo-electric cell of the sound-film projector), or by subjecting it to intense electric fields.

ELECTRIFICATION, OR CHARGING

As we have already mentioned, electric charges consist of displaced electrons. Atoms that acquire an extra electron become negatively charged, while those that lose an electron become positively charged to an equal amount. It is fundamental that whenever a positive charge is created, an equal negative charge is simultaneously created.

Production of the electrified or charged state by rubbing amber, a natural resin, was known to the ancient Greeks. The friction between the surface molecules of two different substances results in the detachment of electrons from the outer orbits of the surface atoms, more such detachments taking place from one substance than from the other, with the result that one material acquires a slight excess of electrons—i.e. is negatively charged—while the other has a slight deficiency and is therefore positively charged. The amounts of charge are of course equal because one substance gains what the other loses.

Separation of charges by friction is the classic way. The modern method is to charge conductors by bringing them into contact with the terminals of a battery or of a mains supply, which shifts electrons directly from one conductor to the other.

Now the two displaced charges exert on each other a force of attraction. They try to coalesce so as to return the system again to electrical neutrality. If the oppositely-charged bodies are held separate, they will attract each other across the intervening space. "Unlike charges attract." In the space will

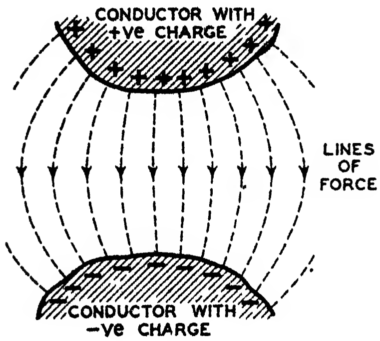


Fig. 2.—Electric Field between Oppositely-charged Bodies.

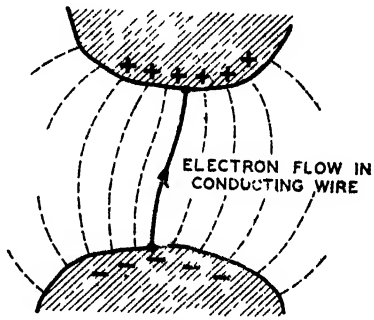


Fig. 3.—Current between Oppositely-charged Conductors.

be found evidence of the attraction, and the useful idea of the *electric field* has been invented to pictorialize this effect, Fig. 2. The direction of the *lines of force* indicates the direction of the mechanical attraction, while the number of lines in a given space is a measure of the strength of the force.

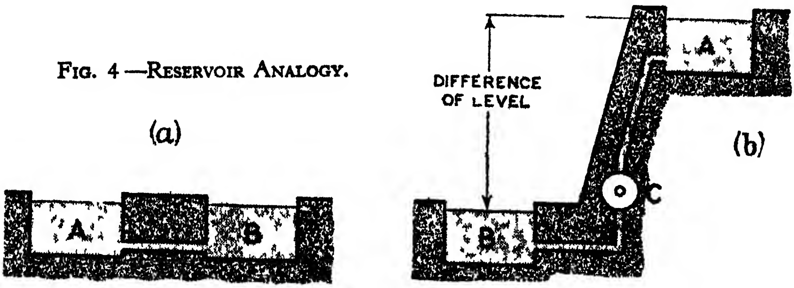
When the charges were separated, the charged bodies had to be pulled apart against the attraction, rather like pulling apart the ends of a helical spring: and again like the spring the *work done* in doing the separation is locked up inside the system as *potential energy*, ready to come out again when the charges are released.

Potential Difference

Because of the energy which has been stored up in the system, Fig. 2, a *potential difference* appears between the two charged bodies. An understanding of the idea of potential difference can best be gained by careful consideration of an analogy in a more familiar guise. Consider two reservoirs,

A and B, containing water at the same *level*, Fig. 4 (*a*). Everyone knows that there will be no tendency for water to run either way along a connecting pipe. But now suppose A and B have a *difference of level*, Fig. 4 (*b*). Clearly the water from A will tend to run down to B through the pipe connection. Further, and most importantly, it would now be possible to insert a water turbine at C—just as is done in a hydro-electric scheme—for the descending water to drive, so that useful work could be obtained. A turbine in the connecting pipe in Fig. 4 (*a*)

FIG. 4—RESERVOIR ANALOGY.



would, of course, produce nothing. What distinguishes the two cases? Not the water, but its *difference in level*. A reservoir system with water *and* a difference in level stores energy and can release it into a turbine.

Now reservoir B might be 1,000 ft. above the sea. If reservoir A is also 1,000 ft. above the sea we are back to the "no energy" case. But if A is 3,000 ft. above the sea it is 3,000 − 1,000 = 2,000 ft. above B, and 2,000 ft. represents the working difference of level on which the storage of energy depends within the system A B.

If in the two paragraphs above the word "level" is read as "potential" the analogy with the separated charges can be more closely appreciated. The parallel is closer still if we imagine that to get the water in reservoir A (Fig. 4 (*b*)) we have to *pump it there from B first*: that would be like pulling the charges apart and storing the energy in the system. The latter is measured in the hydraulic case by amount of water Q multiplied by difference of level V. In exact analogy the energy in the electrical system, Fig. 2, is QV units, where Q is the amount of charge on either body and V is the potential difference—often called the *voltage* because of the units in which

it is measured. Q represents the number of displaced electrons, and V the force urging them together.

In the system shown in Fig. 4 (*b*) we might say that if there are Q lb. of water in A at a height V ft. above B, the potential energy available is QV ft.-lb. Alternatively we could say that V is the energy in ft.-lb. for each lb. of water in A: this would be a direct analogy of potential, which is in joules of energy per coulomb of charge.

Conductors and Insulators

In substances which are known as *conductors*, the outer-shell electrons can be more or less freely interchanged between atoms. In copper, a good conductor, the molecules are held together comparatively rigidly in a kind of framework or "lattice," through which outer electrons from the atoms wander about in large numbers producing a random movement of *free electrons*—rather suggesting the movement of the crowds in an exhibition hall wandering along the aisles, becoming now and then "attached" to a side-show, then moving away again.

The free electrons in a conductor comprise what is called an "electron atmosphere." When electrons are removed from, or added to, a conductor in the process of charging, the deficiency or abundance of electrons spreads over the whole conductor (unless prevented from so doing by some externally-applied electric field).

In other substances called *insulators* all the electrons are more or less firmly bound to their parent atoms, and little interchange of electrons takes place: there is no electron atmosphere.

All material substances, solid, liquid or gaseous, can be classified in a table in which items at one end are good conductors, and items at the other good insulators. In between, there is a very large group merging from conduction to insulation gradually. There is no exact distinguishing line between conductors and insulators. We choose materials suitable for the purpose in hand. Thus for materials having good *conductivity* the metals, especially copper and aluminium, would naturally be selected.

The Electric Current

Now let us look again at the charged electrical system in Fig. 2. The abundance of electrons on the negatively-charged

body attempts to return to make up the deficiency on the positively-charged body. The intervening space must be an insulator to withstand the passage of electrons through it. But now let a conducting wire be placed to join the bodies together, Fig. 3. The electrons of the negative electrode can pass freely along the wire through the molecular lattice and so equalize the charges, dissipate the energy and reduce the potential difference to zero. While the equalisation is going on a *current* of moving electrons runs from negative to positive electrode.

CONDUCTION

Conduction is the name normally given to a movement or flow of charges. The charges are usually electrons, but may also be ions when the conduction takes place in gaseous or liquid conductors, in which the ions are mobile.

A potential difference—that is, an electric field—must be applied to a conductor to cause the charges to move along it, because there is generally some opposition to the flow.

The practical unit of charge flow, or current, is one coulomb moved per sec. past a given point in the conductor. The practical unit is called an *ampere.* In the case of current due to the flow of electrons only, one ampere represents the passage of $6{\cdot}2 \times 10^{18}$ (about six million million million) electrons per sec. In metals this is achieved by the very slow movement of enormous numbers of electrons, while in gases vastly fewer electrons move at much higher speeds.

As has been said, a movement of charge can be a combination of electronic and ionic drift, for example electrons in one direction and positive ions (atoms with a positive charge) in the other. Conventionally the direction of current flow is taken as that of the positive charges and against that of the negative ones.

Conduction in Metals

The two sketches in Fig. 5 illustrate diagrammatically the section of a piece of conducting wire. The white circles are molecules, which maintain unchanged their average position. The black dots are the free electrons. Of course both molecules and electrons are shown vastly larger than they should be. The arrows indicate the directions in which the electrons are

moving at a given instant, and it will be seen that in (*a*) they are moving at random. Some electrons will be moving to the left, others will simultaneously be shifting to the right, and the average shift will be zero; there will be no resultant electron drift and no current.*

Let now a potential difference be applied, as in Fig. 5 (*b*). Every electron now experiences a force tending to make it move to the left. So over and above the rapid random electron motion there will now be discerned a "creep" which is a net movement of charge and therefore a current. The drift is very

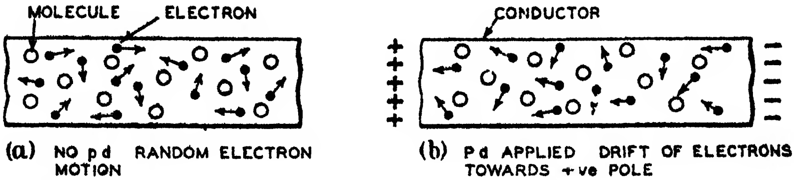


FIG. 5.—ELECTRONIC CONDUCTION IN METALS.

slow—measurable in millimetres per sec.—but so many electrons take part in it that the current may be quite large.

In their high-speed erratic motion the electrons percolate through the labyrinth-like molecular lattice, and collide with it, producing heat. This impedes the flow, giving the effect called *resistance.*

If the temperature of the wire rises, the random motion of the electrons is more agitated, there are more frequent collisions and the resistance is greater.

Conduction in Liquids

This type of conduction depends on whether the liquid is a *non-electrolyte* or an *electrolyte.* In the former, conduction resembles that in metals, except that there are fewer free electrons and so a much more restricted electron flow. Electrolytes, on the other hand, break up into ions, each a part of a molecule and with either one more or one less electron than would give electrical balance. The liquid is therefore full of positively—or negatively—charged masses which are moved bodily when an electric field is applied. A number of interesting chemical

* This describes the effect on the average. At any given *instant* there may be a slight rate of drift one way or the other, a phenomenon of importance in high-gain amplifiers.

reactions take place in the liquid and at the electrodes to which the potential difference is applied. However, electro-chemistry is of no direct application in radio, and nothing further need be said about it here.

Conduction in a Vacuum

This is of extreme importance in electronics and radio, as on it depends the operation of the thermionic valve. Consider a vessel, Fig. 6, completely emptied of gaseous matter, with two metal electrodes across which a potential difference can be applied. This is a *vacuum tube.* In the space between the electrodes an electric field is established, capable of acting on any charges that happen to lie in it. An obvious question is: if the space is truly vacuous, how can there be any charges in it, since charges — electrons, for example—can only be obtained out of atoms of matter? It *is* possible to throw into a vacuum a cloud of electrons, and because the electrons have negligible mass the vacuum will remain unimpaired. Once in the electrode space the electrons must obey the usual laws of attraction and repulsion of electrostatics, and will be urged towards the positive electrode. Because there are no molecules to get in their way the speed attained by the electrons in their passage may be very high indeed—100,000 miles per sec. perhaps.

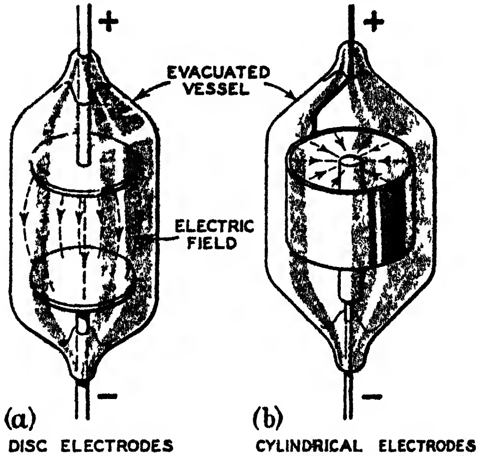


Fig. 6.—Vacuum Tubes.

The motion of a few electrons will give rise to an appreciable current if the speed is high enough, so that the production of an electric current in empty space is perfectly feasible. The radio engineer should be as familiar with the idea of "current through nothing" as with "current through a wire."

Particular interest attaches to the method of injecting

electrons into a vacuous space, and because this is intimately concerned with atoms and electrons, it can profitably be introduced now.

Thermionic Emission.—It has already been stated that a rise in temperature increases molecular activity in a substance. Consider a metal plate or wire forming one of the electrodes in a *vacuum tube*, and suppose it to be heated by some suitable means. The free electrons in the metal become more agitated, and move about in the lattice with increasing speed. Some of those at the surface of the metal move so fast that they break out of the surface confines of the metal into the empty space beyond, only to fall back into the surface again because of the attraction exerted on them. So the heated surface of the metal becomes surrounded with a cloud of electrons, each being ejected from the surface and falling back into it again. This is illustrated diagrammatically in Fig. 7, at the surface of the "cathode," in a tube arranged like that in Fig. 6 (*b*). The process, called *thermionic emission*, produces in the immediate neighbourhood of the heated electrode surface, an *electron space charge*. As might be expected, a rise in electrode temperature means an increase in electronic emission.

This, then, is the most common way in which electrons are made available in a vacuum tube. If a potential difference is applied between the two electrodes to make the emitter electrode negative, the electrons will in part be dragged away from the emitter towards the other receiver electrode, and an electric current is conveyed across the vacuum. The emitter is called the *cathode*, the other electrode is called the *anode*, and the electron stream flows from cathode to anode. (The *conventional* current direction is the opposite of this.)

On arrival at the anode the electrons are absorbed into its surface, and eventually return to the cathode through an external conducting circuit.

The phenomena briefly described are the basis of action of radio valves and cathode-ray tubes, of which technical details are given later in this book.

Photronic Emission.—Certain metals, including the so-called alkali metals, have the property of emitting electrons from their surfaces into a surrounding vacuum when illuminated by visible light. In these cases the energy in the incident light acts as does heat in thermionic emission, and electrons proportional in

number to the amount of light are emitted from the cathode surface, to be caught by an anode held at a suitable positive potential.

Conduction in a Gas

It is always extremely difficult to initiate a current flow through a gas, such as air, at ordinary pressure, because the gas molecules are close enough together to impede the passage of electrons. However, if the gas pressure is very low so that the molecular concentration is sparse, considerably greater currents can be conducted.

Consider, then, a tube like an unpumped vacuum tube, with its gas content being gradually lowered. As pressures corresponding to a few centimetres of mercury gauge are reached, conduction between cold electrodes takes place by the movement in opposite directions of positive and negative ions. Ions are always present to some small extent due to stray radiation, such as light, which causes ionization. At very low gas pressures the electrons produced by chance ionization have much further to travel in the space between the electrodes before colliding with a gas molecule, and as a consequence they attain much higher speeds. This gives them sufficient motional energy to *shock-ionize* neutral gas atoms by impact, resulting in a great enrichment of the electron stream and increased current flow. Under certain conditions the effect becomes cumulative, so that the current becomes very large: it is now called a *spark*, or *arc*, between the electrodes.

The Gas Tube.—A vacuum tube into which a small quantity of gas has been introduced to "soften" the "hard" vacuum becomes a *gas tube*. The gases employed are the so-called inert elements like argon or krypton. Alternatively, vapourized mercury may be used. In each case similar electrical conductive action is obtained, but chemical reactions are avoided.

Fig. 7 illustrates diagrammatically the actions in a gas tube. At the left is the cathode, heated electrically by the passage of a separate heater current. At the right is the anode, and between cathode and anode an electric field is established by external means, making the anode positive to the cathode. The electric field causes electrons from the cathode's electron space charge to be moved from left to right. On their way the electrons (black dots) encounter gas molecules (white circles) and under

suitable conditions of speed will ionize them by collision. We now have positively-ionized gas-molecules (white circles with + signs) and more electrons produced. All the electrons will move to the right, and all the positive ions more slowly to the left. The reason for the more sluggish movement of the ions is, of course, that they consist not of pure charge but of charge associated with mass.

The electrons arriving at the anode are absorbed into it as an electron current. The ions reach the cathode and bombard it, acquiring a negative charge and becoming neutral again, and so contributing an ion current. Some positive ions attract an electron and become neutral before getting as far as the

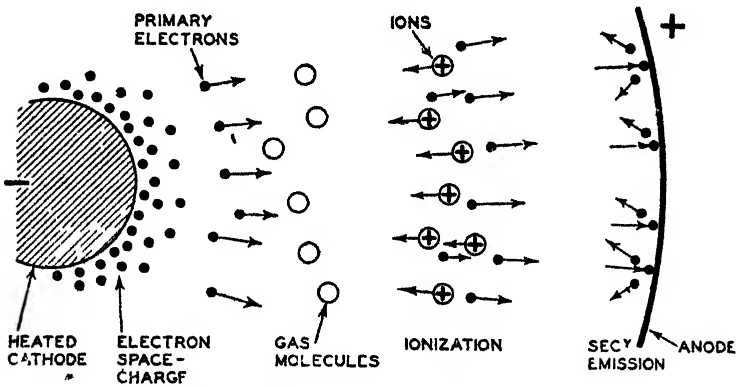


Fig. 7.—Effects in a Gas Tube.

cathode, and so long as current is being conducted ionization and de-ionization are going on in the gas of the tube.

The massive positive ions which bombard the cathode—like bullets their target—always raise the cathode temperature, and on occasion may damage its surface, so vigorous is their onslaught. The impact of the electrons on the anode raises the anode temperature, for although their mass is very small, the electron speed is likely to be very much higher than that of the ions. So long as the electron current is not unduly great it will cause the anode no distress, but the heat must always be adequately dissipated.

Under certain conditions of velocity, *primary* electrons arriving at the anode surface may have the additional effect of "splashing" electrons out of some of the atoms of the anode surface

metal—rather like the effect of dropping a stone into a pool. Such electrons of *secondary emission* normally drop back again to the anode surface because, once released, they are immediately subjected to the same electric field as is driving the primary electrons anodewards.

FORMS OF CURRENT

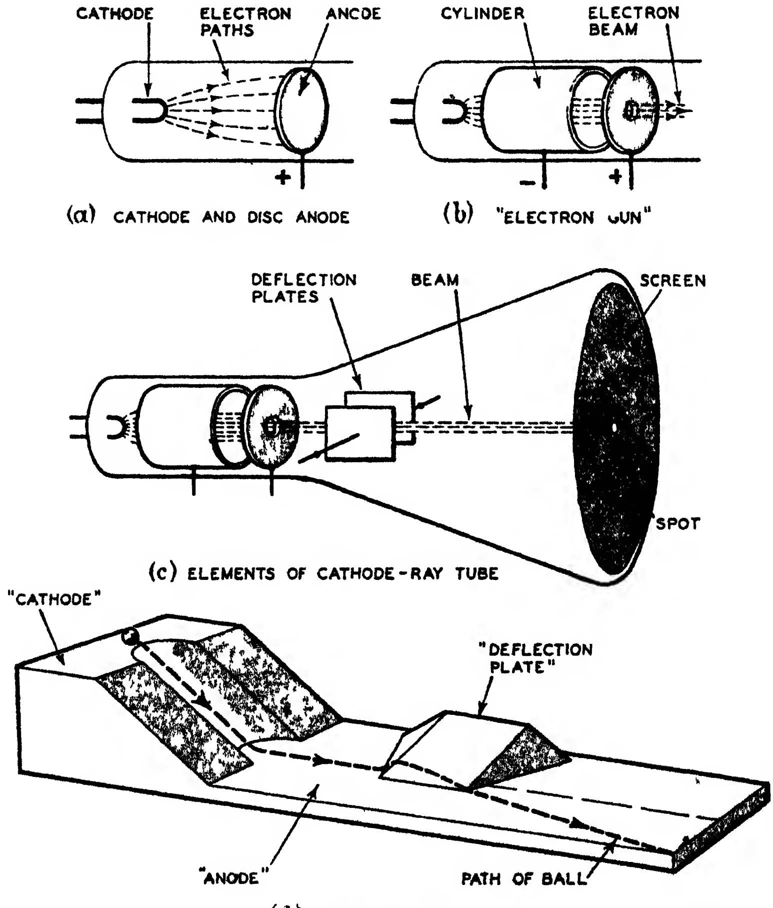
It is possible to produce an electron current along a path having no potential difference. Electrons may be moved on discs, endless belts or water sprays. An example very common in radio is found in the *cathode-ray tube*, which offers a number of interesting features in electron control.

Convection Currents

Consider Fig. 8. At (*a*) is a vacuum tube with cathode and anode as already described. When the cathode is heated it emits, and if the anode is made positive to the cathode by connection to an external electrical supply, electrons will flow at high speed to the anode. The next step is to surround the electron stream by a conducting cylinder given a potential negative to the cathode (*b*). This repels the electrons as they pass, concentrating them into a beam along the central axis. If the anode has a small hole placed centrally, some of the electrons will pass through it at high speed and emerge as a beam continuing on beyond the anode. A convenient analogy is shown in Fig. 8 (*d*). The electrons are represented by small spheres—say ball bearings—and the difference of potential between cathode and anode by a difference in level. Spheres released at the cathode roll down the slope and continue along the flat part like the electron beam. The negative concentrating cylinder has its counterpart in the groove which urges the little spheres into a narrow channel. The spheres continue along " the flat " because of the kinetic energy they have acquired during their roll down the slope. In an analogous way the electron beam beyond the anode continues because of the kinetic energy of the electrons given to them when they are being accelerated between cathode and anode. The cathode-anode system and its auxiliary electrodes (*b*), shown here in a simplified form, is often termed the *electron gun*.

In the cathode-ray tube (*c*) the beam proceeds on until it

strikes a screen coated with a *fluorescent* material. This glows where bombarded by the electrons so that the position of the end of the beam becomes visible. The beam can be deflected by applying a cross electric field between a pair of deflecting plates. As the beam passes between the plates the electrons are attracted by one plate and repelled by the other so that the beam is bent. In the mechanical analogy the ball bearings can be thought of as running across a tilted flap which changes their direction in a very similar way.



(a) CATHODE AND DISC ANODE (b) "ELECTRON GUN"

(c) ELEMENTS OF CATHODE-RAY TUBE

(d) MECHANICAL ANALOGY

FIG. 8.—CATHODE-RAY TUBE

Electrons moving in space under the influence of a previously-acquired velocity, or carried along on a moving belt, etc., are said to form a *convection current.*

Displacement Current

Before proceeding with the consideration of the behaviour of insulating materials, it is necessary to mention here an entirely different kind of current which can be set up without electron flow in empty space. Consider the two conductors in Fig. 9, set up in a perfect vacuum and uncharged. Let them be connected to an electrical supply of low potential difference. Each will then be charged equally, one positively and one negatively. Charging is accomplished by removing electrons from one and supplying an equal number to the other. The charge displacement and the resulting potential difference—see Fig. 2—give rise to (or are accompanied by) the establishment of an electric field in the space between the conductors. Now let the potential difference be raised: more electrons will flow to and from the electrodes and the electric field intensifies. Each time the potential difference *changes,* there is a momentary flow of electrons in the conducting part of the system and a simultaneous change of electric field intensity. The great mathematician, James Clerk Maxwell, suggested that a *change* of electric field might well be considered to be like a current, and that each time the electric

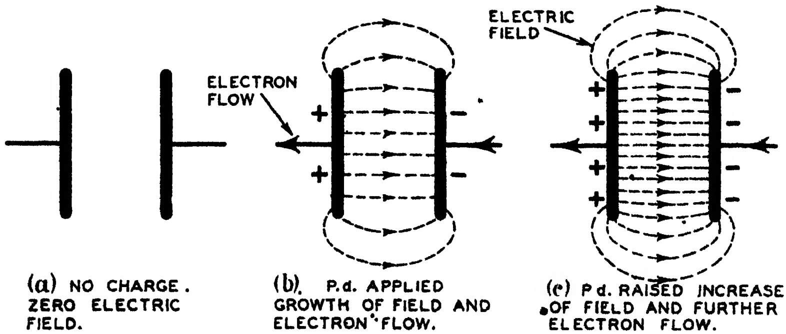


FIG. 9.—CONDENSER CHARGE AND DISPLACEMENT CURRENT.

field increased or decreased anywhere in space, a space current equal to the actual electron flow elsewhere in the system might be *assumed* to occur. This he called *displacement current,* and

it is pure hypothesis. It is nevertheless perfectly true tha displacement current does produce magnetic effects just as doe ordinary conduction electron current. On the hypothesis, witl other experimental laws, Maxwell was able to predict the possi bility of travelling electromagnetic waves—the very stuff o radio. His theoretical work was brilliantly justified by the experiments of Heinrich Hertz.

Polarisation Current

Let us consider the case in which a perfect insulating material —solid, liquid or gaseous—is placed between two conductors across which a potential difference is maintained. The electric field, whose property is to exert a pull on charges, will affect the atoms of the insulating material. Now by definition a perfect insulator has no free electrons. All its electrons are firmly attached to their nuclei. Consequently there can be no general electron drift such as would be found in a conductor. What happens is that the atoms are distorted by a kind of stretching or rotation which displaces the electron orbits and the nuclei in opposite directions. This *polarisation* of the dielectric insulating material may be considered as taking place in the manner indicated in Fig. 10.

The sketch at (*a*) illustrates that before the electric field is applied, the atoms are neutral and unstrained. As the potential difference is raised, the electric field exerts opposite mechanical forces on the negative and positive charges in the atoms, and they become more and more highly strained or rotated (*b*). On their left face the atoms will be negatively polarised, with the opposite polarisation on the right. If the potential difference is removed, the atoms regain their symmetry. Every *change* of electric field intensity changes the relative position of the atom charges and the slight shift of charge is simply a momentary *polarisation current.* This effect is additional to displacement current already considered.

The amount of polarisation that occurs depends on the molecular concentration and on the kind of atom. In gases, the molecules are sparse and the polarisation is small. It tends to be greater in liquids and gases because so many more molecules can be affected in a given space.

The essential difference from the present view-point between a vacuum and a material insulator is that in the former only

displacement current flows, whereas in the latter both displacement and polarisation currents will occur. This leads to the quality of an insulating material called its *permittivity*.

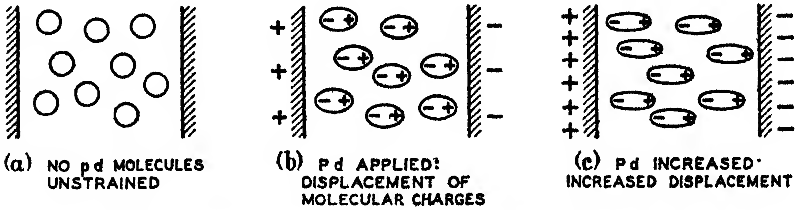


FIG. 10.—MOLECULAR STRAIN AND POLARISATION CURRENT.

The properties of dielectric strain or rotation account for the losses that occur in dielectric (insulating) materials when subjected to changing electric fields. Further, because insulators are never really perfect, a certain amount of actual conduction takes place—although on a vastly smaller scale than in conductors.

We have now come to the end of our outline of the basic ideas of charges and currents. It remains to summarize them and their effects which are of importance in the application of electricity in radio.

Electrical Effects.

In the general outline given above, little has been said about units of measurement and nothing at all about the mathematical-physical aspect of electrical science. For present purposes this can be justified, for a mental concept of what is going on is quite sufficient as a working idea, while numerical values are almost invariably quite simple in the practice of radio as distinct from its theory. What formal theory is necessary will be found in subsequent chapters. Here it is a matter of linking up the electronic idea with the more generally known items of general electrical technology.

The effects of importance in radio, and indeed generally throughout electrical engineering, are these:

1. *Charges at Rest.*—Two charged conductors, separated by a dielectric (insulating) material, have the same amount of charge Q

TABLE I

BASIC IDEAS OF ELECTRICITY

CHARGE	*Fundamental unit* = electron charge (− ve). *Practical unit* = Coulomb = $6{\cdot}3 \times 10^{18}$ electron charges. *Charged particles :* Electron alone (− ve). Positive ion = atom with electron deficiency. Negative ion = atom with electron excess. *Charged conductor :* conductor with electron deficiency (+ ve) or excess (− ve).

TABLE II

CURRENT	*Practical unit* = Coulomb per sec. = Ampere.		
	Physical Nature	Cause	Occurs in
Displacement	Hypothesis	Change of elec. field	All materials and in free space.
Conduction	Movement of electric charges	Applied p.d.	Solids : free-electron movement in molecular lattice. Liquids : as above, or ion movement additionally. Gases : Electron and ion movement. Vacuum : Electron movement if electrons are supplied.
Polarisation		Change of applied p.d.	Insulating materials : atomic strain or rotation.
Convection		Various, other than applied p.d.	Electron and ion movement by mechanical means or inertia.

on each conductor, an associated potential difference V, and a stored energy. The amount of charge for a given potential difference is the ratio $C = Q/V$ called the *capacitance*: it depends on the size of the conductors and their distance apart, and on the *permittivity* K of the dielectric material. The *permittivity* is a matter of the amount of polarization produced. The science of charges at rest is *electrostatics*.

2. *Charges in Motion, or Currents.*—In the space surrounding a current of any sort is found a magnetic field. This effect is very important, as the magnetic field is another kind of energy storage device, and magnetic effects can be produced electrically without the necessity for permanent magnets.

When the current is due to the passage of charge through a conducting material, the material itself opposes the passage and causes collisions which waste energy as heat. The effect is called resistance. In so-called conductors the resistance is low: in insulators it is very high.

3. *Charges in Acceleration, or Changing Currents.*—When current values are suddenly changed their associated electric and magnetic fields undergo a similar sudden change with the result that energy is detached from the system and radiates from it at a velocity which is 3×10^8 metres per sec. in free space. This is electromagnetic radiation, employed as the means of communication in all systems of radio.

Conclusion

After completing this first chapter the reader will have become acquainted with the basic construction of the atom and its relation to the fundamentals of electricity.

Although electrical energy is still an unsolved mystery, we have shown how the application of Rutherford's theory of the nuclear atom to this particular branch of science has provided us with a logical explanation of electrical effects or phenomenon which otherwise had to be taken for granted.

In addition, without the nuclear conception of atomic construction, the thermionic valve, the cathode-ray tube and many other electronic devicés, which have proved of inestimable value, may have taken a great deal longer to develop, as their evolution wo[illegible] entirely dependent upon laborious stages of [illegible]rch work.

[illegible]he field of electronics has provided us

with many improved types of thermonic valves, photo-electric devices and cathode-ray tubes which have contributed to the rapid development of radio, television, radar and many varieties of electronic equipment having industrial, scientific or medical applications such as high-frequency heating, the automatic control of machines and processes, microscopy, radiography, radiotherapy and diathermy.

Electronic equipment such as the cyclotron was also used in the investigations carried out in the structure of the atom, which eventually disclosed a new source of energy and experimental atomic piles to produce and control this energy are now in operation.

CHAPTER II

HOW ELECTRICAL ENERGY IS PRODUCED

THE world's greatest scientists and engineers have devoted years of intensive research to the problems associated with the production of electricity. New types of machinery and equipment are continually being designed, and electricity at very high pressures can now be safely generated and controlled.

In this chapter, the reader will learn of the basic methods of producing electrical energy, but he should bear in mind that these methods have been developed to produce many forms of electrical apparatus to suit specific applications. The generator, of course, is the principal method used for producing electricity for most purposes and, instead of the " rubbing machines " of Wimhurst's day, we have massive turbo-alternators which can furnish current for anything from a lamp to an electrified railway.

The engineer has also harnessed the forces of nature to drive this equipment, and oil, water and coal have been enlisted in this service. Vast engineering undertakings have been successfully carried out to make use of water power, and the principle of the water-mill has been applied to produce the water-turbine, which is used to drive the generating equipment where suitable natural water flows can be adapted.

A typical example of the hydro-electric station is the extensive installation at Muscle Shoals, in the State of Alabama, U.S.A. The huge Wilson Dam, a mile long and 137 feet high, has been constructed across the river Tennessee and harnesses sufficient water power to develop a million horse-power.

In countries where suitable water power is not available, we have to rely on coal or oil fuel, which is employed to produce steam at high pressure. The steam is usually fed to a steam turbine, which is another form of the water-wheel. The turbin[illegible] turn, coupled to an alternator and the current generated [illegible] will be shown [illegible], via the power-house switchboard, and which would otherwise [illegible]

Atomic Energy

Recent researches in this field have opened up vast possibilities. By the use of " fissionable material," e.g. uranium 235 or plutonium in suitably designed " piles " it is now possible to obtain enormous quantities of heat without the necessity of consuming coal or oil fuel. The destruction of a small quantity of U235 will provide the same amount of heat as that obtained by burning many thousands of tons of coal. When the problems of control have been solved, it is probable that " atomic piles " may replace existing boiler plants in generating stations. The turbo-alternating and associated electrical equipment may not need to be appreciably altered.

There are several methods of producing electricity for practical purposes, and each method is by its nature suited to a particular class or range of applications. These applications are very varied, as will readily be understood by comparing some of the familiar everyday uses of electrical energy. At one end of the scale, for example, the battery of a pocket torch may be contrasted with the source of enormous energy represented at the other extreme by a large power station. Both are examples of the application of electrical energy to a particular purpose, and in general the purpose determines the nature of the method used to produce the energy.

The known practical methods of producing electricity may be enumerated as follows :

1. *Chemical,* as represented by the various types of batteries or primary cells in which the electricity is produced by purely chemical actions.

2. *Electromagnetic,* forming the basis of operation of rotating generators in which the electricity is produced by conductors moving through a magnetic field. This is the method employed in practice for generators up to the largest size.

3. *Thermo-electric,* in which the heating of the junction between two different metals produces a very small voltage which may be used for purpose measurement, but is not su power.

4. *Piezo-electric*, in which a very small voltage is produced across certain faces of a crystal by the application of mechanical pressure. This effect is used, for example, as a means of frequency control in radio oscillators or for gramophone pick-ups, but is not suitable for power supply.

5. *Electronic*, characterized by the flow of electrons through evacuated or gas-filled tubes, and having the following forms :

   (*a*) *Thermionic emission*, in which the electrons are produced by the heating of special materials.

   (*b*) *Photo-electric emission*, in which electrons are liberated at the surface of certain substances by the action of light.

   (*c*) *Secondary emission*, in which electrons are driven from a material by the impact of electrons or other particles on its surface.

   (*d*) *Field emission*, in which electrons are drawn from the surface of a metal by the application of very powerful electric fields, such as would exist between the metal and a high-voltage conductor placed very close to it.

It may be pointed out that the various kinds of electronic emission represent cases where electrons comprising the electric current flow through a space, as, for example, in the case of radio valves, in contrast to their passage through solid or liquid conductors as in the other methods of producing electricity. In all cases where electricity is produced the current is due, either directly or indirectly, to the movements of electrons and may therefore be regarded as electronic, but in practice this term is reserved for those forms of conduction in which the electrons traverse a path through a vacuum or a gas. Owing to this special feature of electronic methods, their application involves principles quite different from those applying to other methods of producing electricity, and by electronic means it is possible, as will be shown later, to obtain effects and to achieve results which would otherwise be impracticable.

THE CHEMICAL PRODUCTION OF ELECTRICITY PRIMARY CELLS

The various kinds of primary cells used in practice have their chief application in cases where a self-contained or portable source of electricity is required. A primary cell is suitable for supplying current only for short periods and soon requires renewal if used continuously, also the primary cell cannot be replenished or "recharged" by connection to another suitable source of electricity.

This type of cell, therefore, is used in practice for purposes which require only small currents for short periods separated by relatively long rests. Typical applications are represented by the various forms of electrical signalling systems, ranging from railway signalling to the operation of door-bells and alarm circuits. During recent years, primary cells have for some purposes been superseded by less troublesome and more efficient methods, so that the importance of the primary cell as a source of electricity for practical purposes has been somewhat reduced.

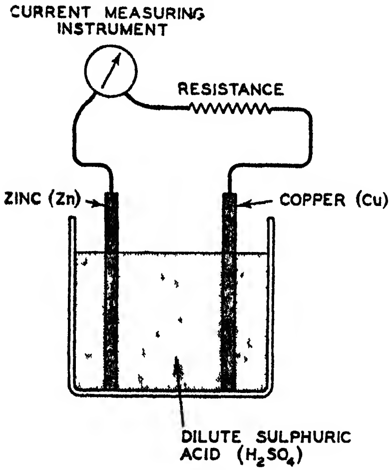


FIG. 1.—ELEMENTARY FORM OF PRIMARY CELL.

All types of cell consist of a vessel containing as essential parts two plates or sets of plates, one corresponding to each terminal, and a chemical solution called the electrolyte, which acts upon the plates so as to produce a voltage at the terminals of the cell. The numerous forms of cell represent the various alternative ways in which these basic components can be arranged.

One of the simplest forms of primary cell consists of a jar containing a zinc plate and a copper plate immersed in dilute sulphuric acid. If an external circuit of some kind including a sufficiently sensitive current-measuring instrument is connected to the plates, as shown in Fig. 1, the instrument will indicate a flow of current, showing that a voltage must be produced between

the plates. At the same time there is a chemical action inside the cell. Without going too deeply into details, it may be said that the zinc (chemical symbol Zn) forming the negative pole of the cell is attacked by the sulphuric acid (H_2SO_4), producing zinc sulphate ($ZnSO_4$) and liberating hydrogen (H_2). This gas collects on the copper plate all the time the circuit is closed, and as its effect is to reduce the voltage of the cell, there is a continuous fall in the current. If the circuit is opened again the gas gradually disperses and the voltage rises eventually to its original value of about 1·2 volts. This effect of the gas in reducing the output of the cell is known as polarisation, and is obviously very undesirable in practice.

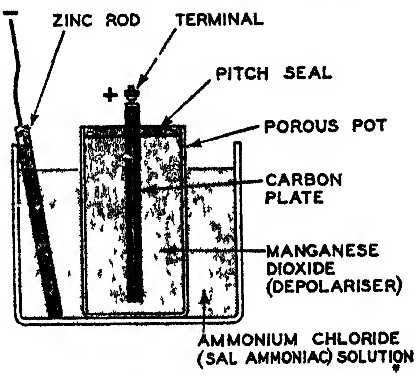


FIG. 2.—LECLANCHÉ CELL, SHOWING SECTION THROUGH POROUS POT.

The Use of Depolarisers

In commercial forms of primary cells, polarisation is prevented by chemical absorption of the hydrogen. This action prevents the progressive fall in voltage and current which would otherwise be caused by the accumulation of hydrogen bubbles.

There are several substances which act in this way as depolarisers, but some of them, such as nitric acid and copper sulphate, which were originally used for the purpose in some forms of cell, are not convenient for general use. A solid depolarising agent surrounding the plate on which the hydrogen would otherwise accumulate is employed in modern cells.

The Leclanché Cell

One of the best known of modern types is the Leclanché cell, having electrodes of zinc and carbon and employing ammonium chloride (sal ammoniac) as the electrolyte. In the original form of cell the carbon plate, surrounded by manganese dioxide as the depolarising agent, is contained in a porous earthenware pot. This pot and the zinc electrode, generally in the form of a rod, are immersed in the electrolyte, the arrangement being as shown in Fig. 2. Although this cell does not polarise and is

suitable for a variety of purposes where small currents are required for short periods, it has a rather high internal resistance which limits the current obtainable. This effect is due to the presence of the porous pot, and in later designs this has been replaced by a canvas bag or sack. In this case the manganese dioxide is moulded in the form of a thick paste on to the carbon plate so as to form a cylinder. This is wrapped in canvas and finally bound with string, making in effect a porous bag containing a central carbon plate surrounded by the depolariser. The construction is thus similar to Fig. 2, except that the porous pot is replaced by canvas.

When a Leclanché cell is in operation the ammonium chloride electrolyte acts upon the zinc electrode, producing ammonia, hydrogen and zinc chloride. The hydrogen moves towards the carbon plate, but first has to pass through the manganese dioxide depolariser in which it is absorbed by chemical combination. This action prevents polarisation of the cell.

Dry Cells

There are many applications for which the so-called wet batteries with a liquid electrolyte are unsuitable, owing to the possibility of spilling, and for such uses the dry cell is extensively employed. This type of cell is made in several forms, ranging from single units of cylindrical shape, about 6 ins. high and 2 ins. diameter, to complete box-type batteries built up from smaller cells and designed for such uses as high-tension and grid bias supplies in radio receivers.

The Leclanché principle is employed, but the electrolyte is in the form of a jelly and the zinc electrode is of cylindrical shape, forming the outside of the cell. The construction is shown in Fig. 3. The depolariser, consisting of manganese dioxide and graphite, is moulded in the form of a thick paste on to the central carbon rod and wrapped with canvas. The zinc container forms the negative pole of the cell,

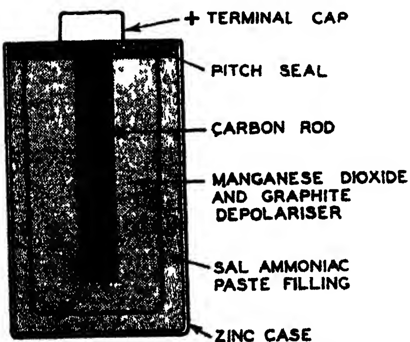


FIG. 3.—SECTIONAL VIEW OF TYPICAL DRY CELL.

and the space between its inside wall and the canvas wrapping of the depolariser is packed with a mixture comprising a jelly base containing sal ammoniac and glycerine. This mixture forms the electrolyte. The construction is completed by sealing with bituminous compound, to give a rigid assembly and prevent entry of moisture.

Owing to the large active area of the zinc electrode, dry cells of this kind have a low internal resistance compared with the conventional wet type, and will supply appreciable currents for long periods. The assemblies of small cells used for high-tension supplies in radio receivers will usually deliver a current of 6 to 10 milliamperes for several hours a day with a reasonable life. The largest dry cells, as used extensively for operating door-bells, will deliver up to about half an ampere for similar periods, and are sometimes used for operating valve filaments. The maximum cell voltage is 1·5, falling to about 1·1 volts at the end of its life. Failure is brought about by erosion and incrustation of the zinc electrode, and the drying up of the electrolyte jelly.

THE ELECTROMAGNETIC PRODUCTION OF ELECTRICITY

There are many cases in practice where it is necessary to convert mechanical energy into electrical energy, and for this purpose use is made of electrical generators of the rotary type, representing a branch of the large family comprising dynamo-electric machines. These machines are driven from a suitable source of power, which may be of any type convenient for the particular conditions of operation, and produce electricity for the extremely wide variety of uses representing modern electrical practice. The design of such generators will obviously vary according to their intended application, but the principles of operation are the same in every case and are in accordance with the relatively simple laws of electromagnetic induction.

The Electromagnetic Production of Voltage

It can be shown by experiment that in any case where a conductor, such as a wire, is passed through a magnetic field so as to cut across the lines of force, a voltage is produced across the ends of the conductor so long as it continues to move. The

effect is the same if the field moves and the conductor remains stationary; the only requirement being that there must be relative movement between the conductor and the field.

The conditions are represented in Fig. 4, where the magnetic field is indicated by the dotted lines between the poles *N* and *S*. The arrows show the direction of the field, assumed by convention to flow from *N* to *S*. For the production of voltage it is necessary that the conductor moves *across* the lines of force. If it were moved along the lines (i.e. up and down in the diagram) this condition would not be met, and no voltage would be produced. The maximum effect is obtained when the motion of the conductor is at right-angles to the lines of force. For any other form of motion a lower voltage is produced, owing to the fact that the voltage is proportional to the rate at which the lines of force are cut by the conductor. For the same reason, the voltage is greater with a stronger field (more lines of force in given space) or with faster movement of the conductor in a given field.

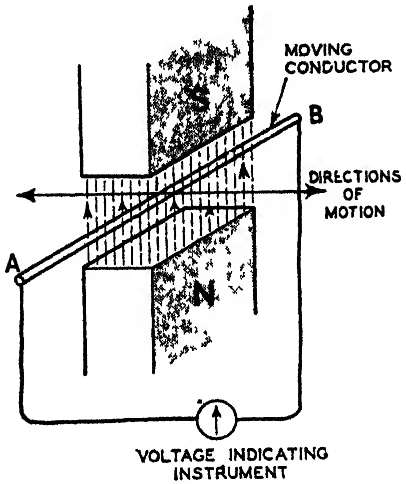


FIG 4.—PRODUCTION OF VOLTAGE BY CONDUCTOR MOVING THROUGH MAGNETIC FIELD.

The Right Hand Rule

If we assume that an instrument capable of indicating the amount and the direction of the voltage is connected to the ends of the moving conductor, as shown in Fig. 4, it is possible to make some important observations. Firstly, we have already seen that the voltage is proportional to the rate of cutting lines of force, and this can be proved by noting that the faster the conductor is moved through the magnetic field, the higher is the voltage, as indicated by the instrument. A similar result can be obtained, without changing the rate of motion of the conductor, by using a more powerful magnet so that more lines of force are intercepted in a given movement of the conductor.

The second important observation is that the direction of the voltage, i.e. the polarity of each end of the conductor, changes according to the direction in which the conductor passes through the field. If the conductor is moved to the right in Fig. 4, end *A* of the conductor becomes positive, so that the direction of the voltage is from *B* to *A* and current flows through the external circuit from *A* to *B*. The directions of the current

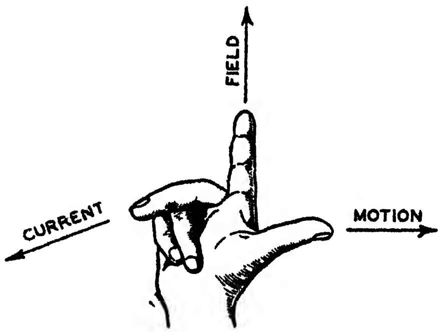


FIG. 5.—FLEMING'S RIGHT HAND RULE.

This is applied for the determination of directions of field, motion and current in a conductor moving through a magnetic field.

and voltage are reversed if the direction of the motion of the conductor is reversed, i.e. if the movement is to the left in the diagram.

It may be noticed that the directions of the three quantities involved: field, motion and the current in the conductor, are at right-angles to each other and are mutually dependent, so that a constant relationship is preserved between them. This relationship may conveniently be remembered by Fleming's *Right Hand Rule,* which says that if the thumb and first two fingers of the right hand are held at right-angles to each other, as shown in Fig. 5, and the index finger points in the direction of the field (i.e. from *N* to *S*), then if the thumb points in the direction of the conductor the second finger will indicate the direction in which the resulting voltage acts, i.e. the direction of the current in the conductor. In all cases where a voltage is induced in a conductor by its motion through a magnetic field, the directions of the three quantities involved are always related in accordance with Fleming's Rule.

The Alternator Principle

The arrangement we have just considered, consisting of a single conductor moved through a magnetic field, would

obviously not be practicable as a means of generating a continuous supply of electricity. For this purpose, a rotary movement is required so that the generating action can be made continuous by using any of the normal sources of power, such as engines or turbines.

A simple arrangement of this kind is shown in Fig. 6 and is seen to consist of a single loop of wire rotated around a central

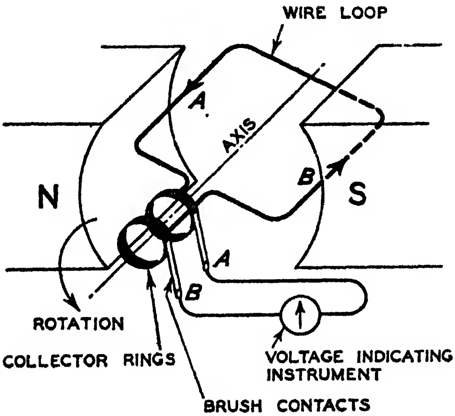


FIG. 6.—ELEMENTARY FORM OF ALTERNATOR.
Illustrating the direction of the current flow in a single loop of wire.

axis between the poles of a magnet. The ends of the loop are connected to two collector rings, or slip-rings, each being in contact with a brush of conducting material. The external circuit, which for the present purpose consists of a voltage-indicating instrument, is connected to the brushes and thus receives the voltage generated by the loop as it rotates on its axis (bearings not shown).

Remembering that the voltage induced in a conductor is proportional to the rate at which it cuts lines of force and that the direction of the voltage depends upon the relative directions of the motion and the lines of force, it is possible to determine how the voltage across the collector brushes varies when the loop is rotated. It is assumed that the speed of rotation is constant. If the direction of rotation is as shown in Fig. 6 side *A* of the loop moves downwards through the field while side *B* moves upwards. Application of the Right Hand Rule will show that this movement causes current flow around the loop as shown by the arrows, the current flowing from brush *A* to brush *B* through the external circuit. Reversal of the direction

of rotation will result in reversal of the direction of the current.

It will be noticed that as the loop rotates, the sides *A* and *B* pass through the lines of force at different angles. When the plane of the coil passes through the vertical position, each coil side is moving *along* the lines of force, so that no cutting occurs and the voltage is zero. In between these positions of maximum and zero voltage, which are seen to be 90 degrees apart, the voltage passes through a succession of intermediate values. The nature of the variation is shown in Fig. 7, and under theoretically ideal conditions, with perfectly uniform field and perfectly uniform speed of rotation, the voltage at any instant, or any part of a revolution, is proportional to the size of the angle through which the loop has rotated, reckoned from a vertical position. In such cases, the machine is said to have a sine-wave output.

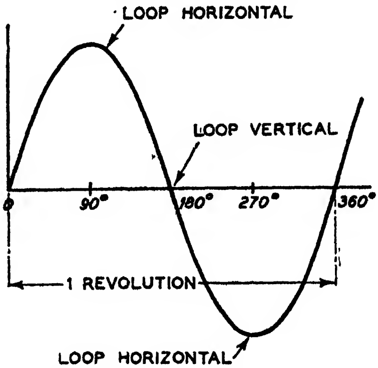


FIG. 7.—VARIATION OF VOLTAGE WITH ANGULAR POSITION OF COIL DURING ROTATION.

Practical Forms of Alternator

Owing to the periodical reversals of voltage and current, these quantities are said to be alternating, and the machine is called an alternator. Machines of this type intended for practical use have a rotating system, or rotor, in the form of a cylinder with a central shaft, the rotor being made of iron so as to obtain the maximum concentration of magnetic field. Consideration will show that the rotation of a solid iron cylinder would cause a current to flow round inside it in the same way as the loop in Fig. 6. In order to minimise the effect of these currents, which represent a loss in causing useless heating of the iron, the rotor is built of thin sheets or laminations, insulated from each other sufficiently to prevent circulation of the so-called eddy-currents. This is a universal feature of the rotating members of practically all electrical machines.

As the rotation of a single loop of wire would give too small a

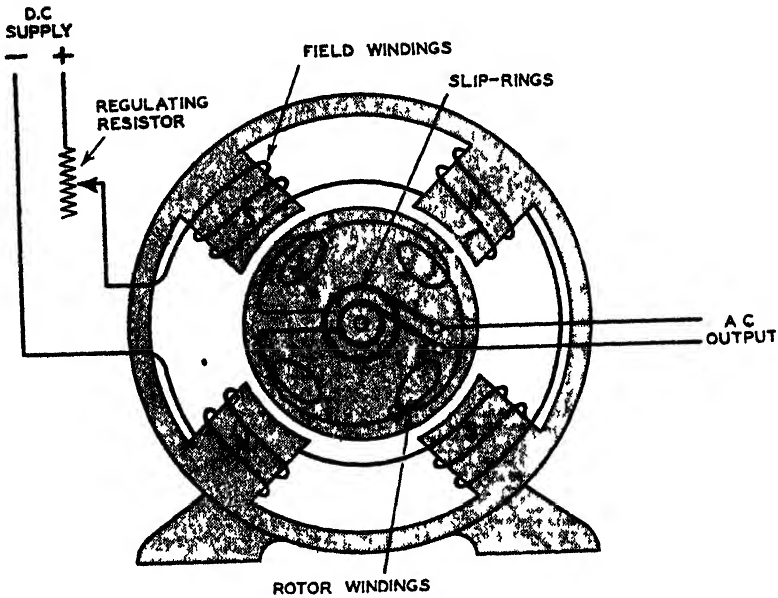


FIG. 8—ARRANGEMENT OF WINDINGS OF SINGLE-PHASE ALTERNATOR
Rotor winding shown diagramatically

voltage for practical purposes, the commercial form of alternator uses rotor coils having a relatively large number of turns. These coils are contained in slots around the outside edge of the rotor and are connected so that their respective voltages add together. An alternator may theoretically have any number of pairs of poles and as a complete alternation of voltage occurs while each winding passes under one pair of poles, the number of complete alternations or cycles per second, known as the frequency, is equal to the number of revolutions per second of the rotor multiplied by the number of *pairs* of poles. The arrangement of the windings in a four-pole, single-phase machine is shown diagrammatically in Fig. 8. Three-phase machines have three separate rotor windings, and use three slip-rings.

In some cases, especially in large alternators, the rotor carries the field system and the alternating voltage is induced in stationary conductors distributed around the inside surface of the fixed member, called the stator. In the majority of commercial alternators the magnetic field is produced by electro magnetic means, i.e. the poles are of soft iron surrounded by windings

(field coils) through which a suitable current is passed. By regulating this current with an adjustable resistor, as shown in Fig. 8, the field strength and hence the output voltage can be varied.

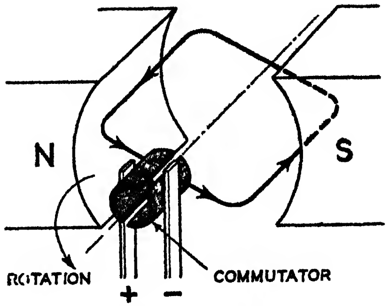


FIG. 9.—ELEMENTARY FORM OF D.C. GENERATOR.

Principle of the D.C. Generator or Dynamo

For many practical purposes, alternating currents and voltages are not suitable and it is necessary to have a machine that will produce a unidirectional output resembling that of a battery. Direct-current generators of this kind depend upon the same principles as alternators, with the essential difference that a commutator is used instead of slip-rings. The action of the commutator is to ensure that the current supplied to the outside circuit flows always in the same direction.

The basic form of D.C. generator is shown in Fig. 9, from which it is seen that the commutator consists of two separate parts, called segments, making contact alternately with a pair of collector brushes located opposite each other. The arrangement is such that each brush changes contact from one segment to the other every time the armature coil passes through the position of zero voltage, which is twice in each revolution (plane of coil vertical). The sequence of diagrams in Fig. 10 shows that, starting from position (*a*) the left-hand brush is positive when the rotation is as shown, coil-side *A* moving downwards. When position (*b*) is reached, the voltage and current are zero and the gaps between the commutator segments are bridged

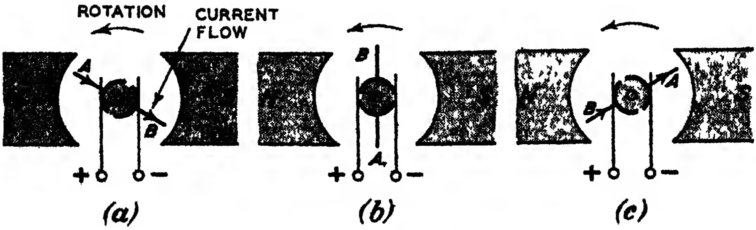


FIG. 10.—ACTION OF COMMUTATOR IN SIMPLE D.C. GENERATOR.

by the brushes. Further movement in the same direction results in coil-side *A* being connected to the right-hand brush instead of the left-hand brush, and the current flows from the coil into the external circuit in the same direction, as shown at (*c*). The form of the output voltage is seen to be as shown in Fig. 11, i.e. a series of pulses, each occupying half a revolution of the coil. If the speed of rotation is constant the pulses are of identical size and shape. Comparison with Fig. 7 will show that the introduction of the commutator in effect reverses every alternate pulse of voltage, thus ensuring that the current flows always in one direction from the machine.

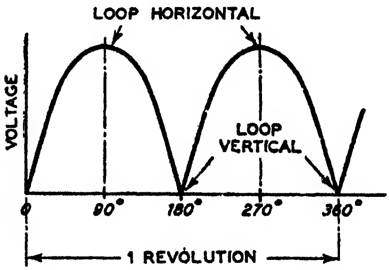


FIG. 11.—ACTION OF COMMUTATOR IN GIVING UNI-DIRECTIONAL VOLTAGE.

Although the current is uni-directional, the sequence of pulses comprising it is only a rough approximation to the smooth output of a battery, representing the ideal form of direct current. In practice, the output is made smoother by using a large number of coils on the rotating member, called the armature, and a correspondingly large number of commutator segments. In this way, the output voltage becomes the sum of a large number of individual voltage waves or pulses, and as these voltages are picked up in sequence by the brushes during rotation of the

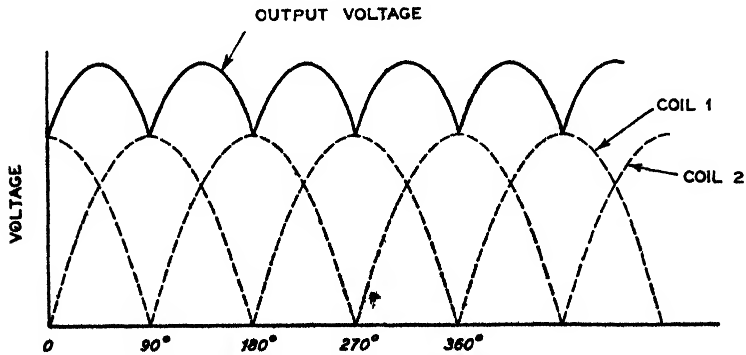


FIG. 12.—VOLTAGES PRODUCED BY TWO ARMATURE COILS AT RIGHT-ANGLES.

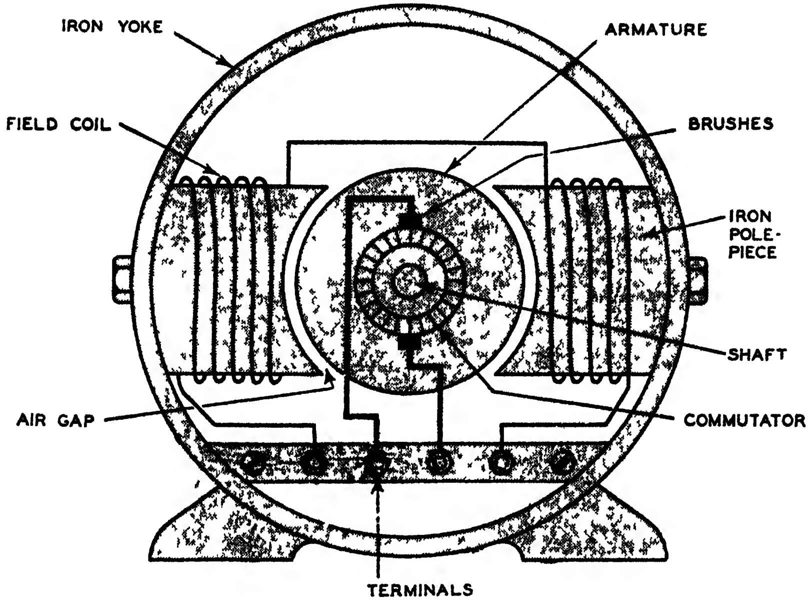


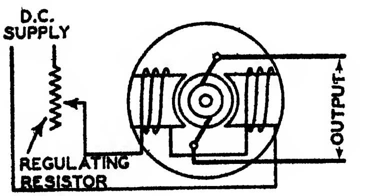
FIG 13—ARRANGEMENT OF TWO-POLE D C GENERATOR.
End bearing bracket removed.

armature, the output voltage takes the form of a ripple. The conditions are shown in Fig. 12 for the case of two armature coils at right-angles to each other. The dotted curves show the individual coil voltages and the full line is the sum of these voltages, representing the voltage at the brushes. It is evident that with a large number of coils the wavy form of the output voltage will be less pronounced. In commercial forms of generator the voltage ripple is generally very slight.

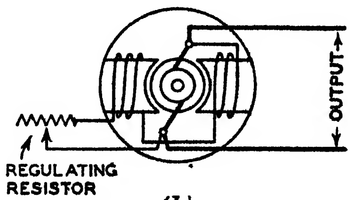
Practical Forms of Dynamo

The arrangement of a typical D.C. generator is shown in Fig. 13. This is a two-pole machine, with two collector brushes and two pole-pieces as shown. The armature is built up of thin iron laminations so as to minimise eddy-current heating and losses. The air-gap between the pole faces and armature is made as small as practicable so as to obtain the maximum magnetic field. The armature coils are located in slots round the outside edge of the armature. The magnetic field is provided by the field coils mounted on the pole-pieces.

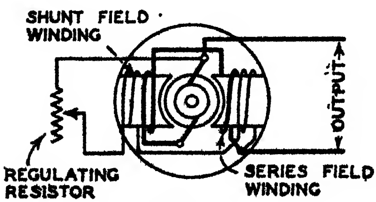
There are several ways in which the field coils may be connected, as shown by the diagrams in Fig. 14. Separate excitation, in which the field coils are connected to an indepedent source of supply, such as a battery, as shown at (*a*), is used only for special purposes. The magnetic field strength, and hence the output voltage for a given speed, can be varied by means of the regulating resistor, which determines the exciting current. The shunt-wound dynamo, connected as at (*b*), is frequently used. The field windings are connected across the armature, and as there is no separate source of excitation, the machine relies upon the small amount of field which remains in the iron circuit when the machine is stationary to produce a continuously increasing voltage as the armature runs up to its normal speed. Without this so-called residual magnetism the shunt-connected dynamo would not begin to generate. In the compound-wound dynamo shown at (*c*) a winding in series with the armature, and therefore carrying the load current, is used in addition to the shunt field winding. By connecting the series windings to assist the shunt, i.e. so that an increase of current increases the field strength, the field and hence also the output voltage is augmented with increasing load on the machine. For this reason, the compound-wound dynamo has a smaller drop in output voltage than the shunt-wound type when the load is increased. By suitable compounding it is possible to obtain a level characteristic,



(*a*)



(*b*)



(*c*)

FIG. 14.—ALTERNATIVE CONNECTIONS. OF D.C. GENERATORS.

(*a*) Separately-excited dynamo.
(*b*) Shunt-wound dynamo.
(*c*) Compound-wound dynamo.

with which the output voltage remains steady irrespective of the load, or even a rising characteristic, with which the voltage increases with the load.

Numerous other arrangements of connections have been developed for special purposes, but they are largely extensions of the basic principles which have been described and may be understood by careful application of these principles.

THERMO-ELECTRIC EFFECTS

Experiments have shown that some rather curious effects occur when different metals are placed in contact with each other. The effects are very slight, and can be detected only with sensitive apparatus, but they are important in various branches of electrical practice. It is found, for example, that if a circuit is formed by joining together two wires of different materials, the heating of one of the junctions or joints will cause the appearance of a small voltage across this junction. The actual value of this voltage, measured in millivolts (thousandths of a volt), is roughly proportional to the difference in temperature between the heated junction and the cold one, as will be seen from the following figures relating to three typical combinations of metals :

Hot Junction Temp., °C. (Cold Junction 0°C.)	Voltage (Millivolts).		
	Chromel-Alumel.	Iron-Eureka.	Copper-Eureka.
100	4·1	5	4
200	8·1	11	9
300	12·2	16	15
400	16·4	22	21

If sufficiently sensitive means are available for measuring these voltages, it is evident that a suitable junction of this kind can be used to measure temperature ; the voltage being a direct measure of this quantity. When used for such purposes the junction is called a thermocouple.

Use of Thermocouples

There are several types of thermocouples which have been developed for special applications, such as the measurement of radiant heat or surface temperatures. They have the advantage of being applicable in cases where other methods would be unsuitable or inconvenient and are widely used in industry for the accurate measurement and control of temperatures up to about 2,000° C. As thermocouples can be made very small, it is possible to use them in inacessible places, as for example under the sparking plugs of aircraft engines so as to provide an indication of engine temperature. They are also particularly useful in research work on processes involving heat treatment, such as the manufacture of tyres, where the couples can be assembled into various positions in experimental tyres, and a range of temperature readings taken during the actual heat treatment.

An important application of thermocouples in radio work arises from their use in measuring instruments. The principle is shown in Fig. 15, where the ends of a thermocouple C are connected to a milli-voltmeter V, the thermocouple itself being in contact with a wire W carrying the current to be measured, which is conveyed to the instrument through terminals $T1$ and $T2$. The heat developed in wire W, and also its rise in temperature, will be proportional to the square of the current and since the voltage produced by the thermocouple is proportional to the temperature of wire W, the reading of the instrument V will be proportional to the square of the current being measured. The material of the wire W is usually eureka or other high-resistivity alloy and the thermocouple iron and eureka, these metals giving a good E.M.P. and they are also easy to spot weld.

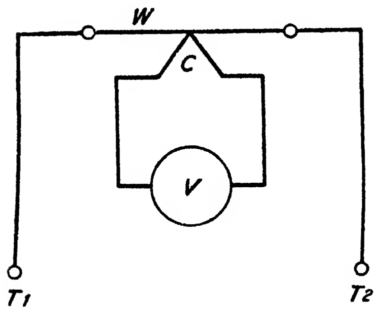


Fig. 15.—Use of Thermocouple in Measuring Instrument.

Such instruments can be calibrated for either D.C. or A.C. measurements, and are widely used for radio frequencies. They have the moving-coil type characteristics of good damping, but may be sluggish due to the thermal capacity of the heater wire.

PIEZO-ELECTRICITY

The crystals of certain materials, notably quartz, tourmaline and Rochelle salt have the peculiar property of developing a small voltage when subjected to mechanical pressure. If the pressure is replaced by tension, the direction of the voltage is reversed. It is also found that if a voltage is applied to the crystal it contracts or expands according to the direction of the voltage. The strength of these effects depends upon the direction through the crystal in which they are applied, and a somewhat elaborate technique has been developed for cutting from a crystal the sections having maximum sensitivity. The name piezo-electric by which these effects are known is derived from the Greek word " Piezein," to press.

Each crystal section has a natural frequency of vibration, which is approximately the frequency at which it operates in radio circuits when used as a means of controlling an oscillator. The natural frequency varies with the thickness of the section, becoming higher as the thickness is decreased. Crystals having natural frequencies ranging between about 25 kc/s and 5 Mc/s represent normal practice, but the technique of manufacture is continually changing, and much higher frequencies are sometimes provided for. An upper limit is set by the thinness of the section, which may make it unduly fragile.

Practical Applications

The principle use of crystals is for controlling the frequency of oscillators within very close limits. For this purpose, the crystal is mounted in a special holder which allows the application of the exciting voltage. This voltage is oscillatory and sets up vibration of the crystal. If the frequency of the applied voltage is in the region of the natural frequency of the crystal the amplitude of vibration is large, and a correspondingly large voltage induced by the mechanical movement appears across the crystal faces. This voltage can be applied to the grid circuit of a valve so as to sustain oscillations in an associated circuit. The great advantage of the crystal method in controlling oscillations is that it is not so dependent upon the constancy of the properties of the controlled circuit. Changes of natural frequency due to temperature can be minimised by cutting the crystal section in a particular way. Temperature control of the crystal is also used where great accuracy is required.

THE PRODUCTION OF ELECTRON CURRENTS

It now remains to consider the various ways in which electrons may be liberated or extracted from solid conductors so as to form a current flowing through the adjoining space to other conductors. The production of currents in this way forms the basis of the science of electronics and is fundamental to all branches of radio technique.

Thermionic Emission

It was found many years ago that a heated filament inside an evacuated glass bulb gave off a negative charge which could be collected under suitable conditions by another electrode inside the bulb. The electrons comprising the charge were evidently driven from the filament purely by the action of the heat, and the effect became known as thermionic emission.

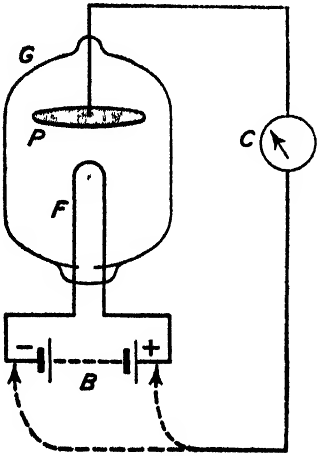


FIG. 16.—APPARATUS FOR DEMONSTRATING THERMIONIC EMISSION.

The basic facts of this form of emission can be shown with the simple apparatus in Fig. 16. The evacuated glass envelope *G* contains a metal plate *P* and a filament *F* formed by a wire which is brought to a high temperature by the current from battery *B*. The plate *P* is connected to one terminal of a current-indicating instrument *C* and the other terminal of this instrument is arranged for connection to either the negative or positive side of the battery, as shown by the dotted lines. It is found that when the connection is on the negative side the instrument reading is zero, showing that no current flows to plate *P*. When the connection is on the positive side of the battery there is a reading of instrument *C*, provided that it is sufficiently sensitive to measure the very small current which flows to the plate under these conditions. It is seen from this experiment that current flows to the plate only when it is positive with respect to the l ament, and since only unlike charges attract each other

it is inferred that electrons released from the filament and attracted to the positive plate are responsible for the plate current.

Considerable attention has been given to the problem of how electrons are driven from a metal by the action of heat. The modern view is that a metal contains, in addition to its normal atomic structure, a number of free electrons which move about at random in all directions, but experience powerful forces tending to pull them back into the metal when they approach its boundaries. As the temperature of the metal is raised, the agitation of these electrons is increased and eventually reaches a stage where the restraining forces are overcome and the electrons leave the metal freely. They may then be attracted by a positive electrode in the vicinity so as to constitute a current as already explained.

These principles are embodied in a variety of types of thermionic cathodes for use in radio valves which are discussed in detail in Chapter XI and a wide range of other electronic apparatus as a means of providing a source of electrons. In many cases use is made of indirectly heated cathodes, in which the emission does not take place from the filament itself, but from a separate electrode heated by the filament. Specially prepared materials with a high rate of emission are used for the cathode surfaces.

Photo-electric Emission

Under suitable conditions, it is possible to produce an electric current simply by allowing light to fall on a metal surface. In order to obtain measurable results it is necessary to use special metals enclosed in a highly evacuated bulb, and even then the current is measured in microamperes (millionths of an ampere). This small current is composed of a stream of electrons which leave the metal surface under the impact of illumination and are collected by a second electrode which is made positive with respect to the emitting surface so as to form a source of attraction for any electrons in its vicinity. The conditions are, in fact, similar to those applying to thermionic emission, except that light is the cause of the electron emission, and not heat.

The conditions are represented in Fig. 17, which shows the emitting electrode or cathode *C* and the anode or collecting

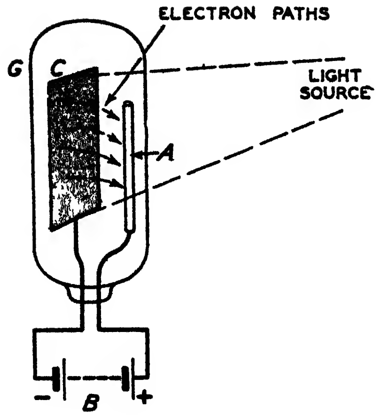


FIG. 17.—PHOTO-ELECTRIC EMISSION OF ELECTRONS UNDER THE ACTION OF LIGHT.

electrode *A* enclosed in an evacuated glass envelope *G*. A battery *B* serves to maintain the anode at a suitable positive voltage with respect to the cathode. If light falls on the cathode, electrons are ejected from its surface and become attracted by the anode so as to constitute a current in the external circuit as long as the illumination is maintained. The rate at which electrons are emitted, and hence the current, depends on the amount of light, and is different for dissimilar materials. These are generally the alkali metals, among which cæsium, barium, potassium and sodium are widely used in practical forms of photocells embodying these principles. Each metal behaves differently with light of different colours and, in general, each gives a maximum emission at a particular colour.

Emission type photocells, which are used in various branches of industry and form the basis of television and the sound-film are dealt with in Chapter XXIII.

Secondary Emission

If an electron or an ion strikes an electrode with sufficient velocity the impact may cause the ejection of one or more electrons from the surface. These electrons are shaken loose in some way from the restraining forces which normally keep them within the surface of the material, and under suitable conditions as many as ten electrons may be liberated by one impact. As in other forms of emission, the behaviour of these secondary electrons as they are called depends upon the conditions in the region of the emitting surface. They can be attracted by a positive electrode and utilized in an external circuit, where the current will depend upon the number of electrons striking the emitting surface and the number of secondary electrons produced by each impact.

The principles of secondary emission are shown in Fig. 18, where *E* is the emitting surface and *A* the collecting anode which is maintained at a suitable positive voltage by battery *B*. It is assumed that the source of primary electrons is contained within the same evacuated glass envelope *G*. The impact of each primary electron liberates a number of secondary electrons which are attracted to the anode and constitute a flow of current which may be measured by the sensitive instrument *C* connected in the anode circuit

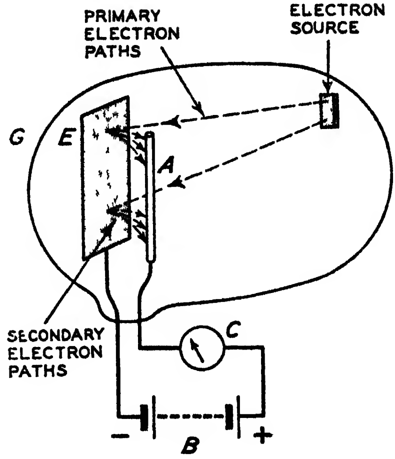


FIG. 18.—SECONDARY EMISSION DUE TO IMPACT OF ELECTRONS.

The effects of secondary emission are very undesirable in many forms of electronic apparatus. In valves, for example, there may be secondary emission from the grid, which will cause an unwanted increase in anode current, and special measures are sometimes necessary to prevent this trouble. The electron multiplier, described on page 542, is an example of the way in which secondary emission may be usefully employed to obtain very large magnification of feeble electron currents.

Field Emission

It is possible to draw electrons from a material by placing close to its surface a high voltage conductor which is positive with respect to the surface. A voltage of the order of a million volts per centimetre of distance between the two electrodes is necessary to produce the effect, which accordingly has little interest from the practical viewpoint.

The effect can be obtained at temperatures much lower than required for thermionic emission and is consequently referred to sometimes as the cold cathode effect. The terms cold emission or auto-electronic emission are also used.

As electric fields are strongest between conductors which are close together and have sharp points or edges, these are the conditions favourable to field emission which may occur with

voltages as low as 200 if sharply pointed electrodes are used with a sufficiently short gap. In cases where electrodes having opposite potentials are of necessity very close together, the possibility of field emission can be minimised by avoiding sharp edges or corners on adjacent surfaces.

CHAPTER III

HOW ELECTRICAL ENERGY IS USED

THE numerous practical applications of electricity may be broadly classified according to the effects produced, so as to divide the subject under the general headings of Heating, Lighting, Power, Electrochemistry and Communications. Although it is only the last of these groups which concerns us directly in this book, modern radio communication technique employs many principles belonging to the other groups, and an adequate background of these subjects is therefore essential to the study of radio engineering. In this chapter consideration is given to the basic principles underlying the various uses of electricity outside the sphere of communications so as to provide an introduction to the general forms of electrical apparatus used in modern practice.

ELECTRICAL HEATING

It was found at a very early stage of electrical progress that when a current is passed through a wire there is an increase of temperature of the wire. The heating increases as the current is increased, and for a given value of current, thinner wires become hotter than thick ones. These principles are embodied in the ordinary household type of rewireable fuse, the wire in which is heated sufficiently to cause it to melt when a particular current, known as the fusing current, is exceeded. Thin wires of a given material have lower fusing currents than thick ones.

Another familiar example of the use of this kind of electrical heating is represented by the so-called electric fires or radiators, and the same principle is used in electric irons, kettles, immersion heaters and a variety of other forms of heating apparatus. In all applications of this kind, it is necessary for the wire to withstand a high temperature for long periods. As the heat developed for a given current is proportional to the resistance of

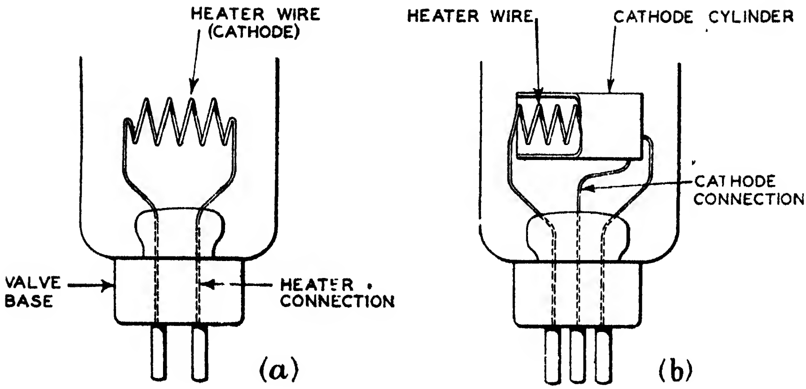


FIG. 1.—ALTERNATIVE ARRANGEMENT OF VALVE CATHODES (SIMPLIFIED) USING RESISTANCE HEATING PRINCIPLE.

the wire, it is also necessary for the resistance to be high. Several special alloys have been developed combining these properties and others which are necessary in particular uses. The resistance of the special alloy wires depends upon the particular metals used, and varies from about 20 to nearly 100 times the resistance of copper wires of the same thickness.

Temperature Coefficient of Resistance

When the temperature of a conductor is raised, either by passing current through it or heating it externally, the resistance increases in proportion. The amount by which it increases for each degree of temperature is called the temperature coefficient of resistance. For the majority of materials the coefficient is positive, that is, the resistance rises with increasing temperature, but there are a few substances, notably carbon, which have a negative coefficient, so that the resistance is lowered with increasing temperature.

The value of the temperature coefficient of resistance for a wide range of materials is approximately 0·004 per degree Centigrade, which means that the resistance of the material rises 0·4 per cent for each degree Centigrade rise of temperature. This rise of resistance means that a hot conductor passes less current for a given voltage than when it is cool. Although in many cases the effect is of little importance, there are other applications in which it would be very undesirable to have the

current varying according to the temperature of the resistance wire. For such purposes special alloys have been developed having an almost negligible coefficient, so that resistance changes due to temperature variation are practically eliminated.

Valve Cathodes

Electrical resistance heating is the method universally employed for the operation of heater filaments in the various types of thermionic valve (see Chapter XI). For this purpose it is by far the most convenient arrangement, as only two wires need to be brought out to the valve base for conveying the heating current, and as long as the applied voltage remains constant the temperature of the filament inside the valve will also be constant when the final value of temperature has been reached after switching on. The basic principle is shown in Fig. 1, where (a) refers to a directly heated cathode, in which the heater wire itself acts as the cathode, while (b) shows an indirectly heated cathode. In this case, the cathode is electrically independent of the heater wire or filament, from which it receives its heat by radiation. One important advantage of the indirectly heated cathode is that an A.C. supply may be used for the heater without causing hum in the valve output due to the rapid alternations of heater current.

Resistance Welding

If a current is passed through two conductors which are in contact with each other, as shown in Fig. 2, the region of the contact between them becomes heated. If the current is sufficiently high, the heat generated may in certain cases be sufficient to weld the two conductors at the region of contact. This is a further example of resistance heating, the resistance in this case being in the contact between the conductors. A contact resistance of this kind is generally high in relation to the resistance of the conductors themselves, so that most of the heat is generated in the contact region.

These effects form the basis of resistance welding as a means of joining metals simply by placing them in contact and passing a suitable current between them.

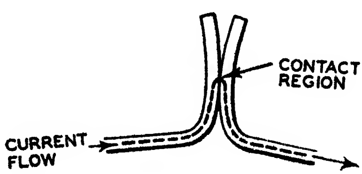
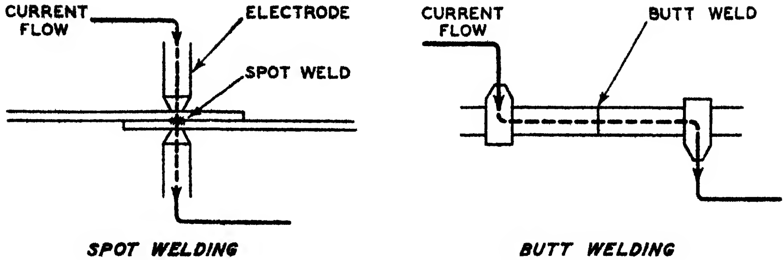


Fig. 2.—Current Flow Between Two Conductors Causes Heating in the Contact Region.



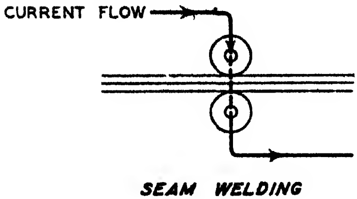


Fig. 3.—Alternative Forms of Resistance Welding.

Sufficient heat is generated at the regions of contact to weld the conductors together.

There are several forms of resistance welding, corresponding to the different ways in which the current and mechanical pressure can be applied. In spot welding, for example, the materials to be joined are pressed together between two tapered electrodes. The current is then switched on for a sufficient period to give the welding temperature so that the materials are joined under the pressure of the electrodes. The current is then switched off and the electrode pressure released, leaving a small welded region.

This method of welding is widely used in the manufacture of radio valves, where light metal parts have to be joined together neatly and quickly. The principle of the method is shown in Fig. 3, together with the arrangements for butt welding, used for joining rods or wires end-on, and seam welding, in which the current passes to the work through rollers so as to make a continuous joint. Pulses of alternating current are generally used in these methods of welding, but various techniques have been developed for different classes of work.

The Arc

If two electrodes or contacts between which a current is passing, as in Fig. 2, are slowly separated, an arc may form between them through which the current continues to flow. The voltage across the arc increases with the arc length, being

about 25 volts per inch in the case of copper electrodes under normal atmospheric conditions. The current density in the arc, i.e. the number of amperes per unit cross-section of the arc, generally lies between 600 and 62,000 amperes per square inch. Arcs drawn between carbon electrodes in air were at one time widely used as sources of illumination, but to-day the use of the electric arc is confined mainly to arc welding and arc furnaces. These applications, which employ very heavy currents, make use of the heating effects of the arc, which is very considerable when suitably applied.

Arc Welding

In this form of welding one connection is taken to the work itself and the other to a movable electrode, the arc being drawn between these two members, so that by moving the electrode the operator can direct the intense heat of the arc to any desired region of the work. The principle is shown in Fig. 4. Either direct or alternative current may be used, according to the nature of the work. Sometimes a filling metal is melted into the joint and in other cases the electrode itself forms the filler as the weld is made. Currents of several hundred amperes are normally used, and the whole technique is now highly specialized owing to the wide variety of materials and forms of weld which may be required.

Arc Furnaces

In the arc furnace, the heat of the arc is used to melt a charge of metal held in a container with a heat-resistant lining and arranged for pouring the charge into moulds for casting

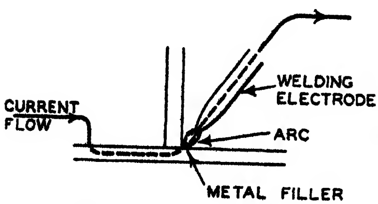


FIG. 4.—PRINCIPLE OF ARC WELDING.

The illustration shows the method of welding two plates together by running the filling metal into the joint.

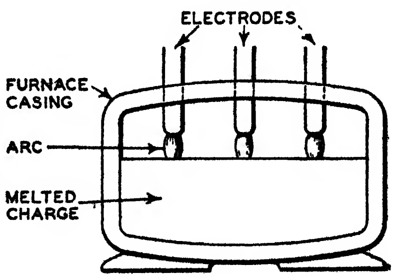


FIG. 5.—PRINCIPLE OF ARC FURNACE.

purposes, etc. Three-phase alternating current is generally used, the arcs being struck between the three electrodes and the metal charge as shown in Fig. 5. The electrodes are of carbon or graphite, and burn away continuously while the furnace is in operation. The correct distance between the electrode tips and the surface of the charge is usually maintained by automatic means.

Furnaces of this type are made up to about ten tons capacity with electrodes about ten inches in diameter and taking a current of 10,000 amperes or more. These high currents necessitate special circuit arrangements and very heavy conductor systems, part of which must be flexible to allow tipping of the furnace when the charge is poured.

Eddy Current Heating

If an alternating current is passed through a coil which encloses a piece of metal, the continuous reversals of magnetic field through the coil produce currents in the metal which raise its temperature. This effect is well known and has to be allowed for in the design of A.C. apparatus in all cases where alternating magnetic fields act upon conducting materials. These induced currents always occur in apparatus where alternating fields are produced in iron circuits, such as the field circuits of A.C. motors, and therefore, in these instances, the magnetic circuit is built up from thin iron laminations so that the paths of the induced eddy currents, as they are called, are restricted by the resistance presented by the individual laminations instead of having the low resistance path corresponding to a solid iron circuit.

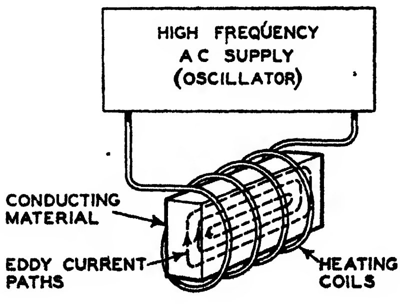


Fig. 6.—Arrangement for Eddy Current Heating of Conducting Material.

Frequency Ranges

The heating effect of eddy currents increases as the frequency of the field alternations is increased, so that the production of heat for practical purposes by this method generally employs currents of high frequency. In practice, the frequencies used range from about 20 kilocycles (20,000 cycles) per second to a

megacycle (1,000,000 cycles) per second, which may be compared with the mere 50 cycles per second of ordinary A.C. supply circuits. The high frequencies required are obtained from specially designed oscillators employing large thermionic valves with a high-power output. The principle of the method is shown in Fig. 6.

It will be understood that eddy current heating can only be applied to conducting materials, as insulating materials cannot have eddy currents produced in them. The practical importance of eddy current heating arises from the fact that it is highly efficient, the heat being produced actually inside the body undergoing treatment, and may be applied for purposes, such as localized heating, which would be impracticable with ordinary methods.

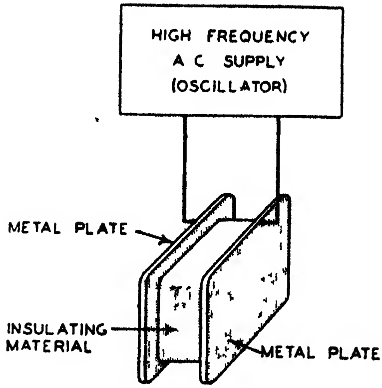


FIG. 7.—ARRANGEMENT FOR DIELECTRIC HEATING OF INSULATING MATERIAL.

Capacity Current (Dielectric) Heating

It is found that when an insulating material is placed between two metal plates, as shown in Fig. 7, and the plates are connected to a source of high frequency, the material becomes heated. This effect may be explained as being due to the strong agitation between the molecules forming the substance under the rapidly changing electric field between the plates. This agitation sets up friction, forming a source of heat within the material.

Dielectric heating is widely used in the preparation and treatment of plastics and for the bonding of ply woods and similar materials, which can be set into desired shapes by means of clamps or moulds while undergoing the heat treatment. Frequencies as high as 200 megacycles are used in some applications. The fact that the heat is generated within the substance being treated is of great value in many instances, as a much greater uniformity of heat distribution can be obtained, in comparison with the older conventional methods where the heat reaches the interior by conduction. Also, with dielectric heating, overheating of the surface layers, while the centre is relatively cool, is eliminated, resulting in a more uniform product.

ELECTRIC LIGHTING

The filament type lamp, now almost universally employed for lighting purposes, makes use of the heating effect of a current passing through a conductor in order to raise the conductor (forming the filament) to a state of brilliance. If such a high temperature was reached in air the filament would rapidly burn away, so that, in practice, it is enclosed in a glass bulb which is either highly evacuated or filled with an inert gas, i.e. a gas such as argon or nitrogen which does not enter into chemical action with the filament.

As the gas has a cooling effect on the filament which must be offset in order to maintain efficiency, the filaments of gas-filled lamps are coiled into a close spiral as shown in Fig. 8. This arrangement results in the trapping of heat between adjacent spirals and gives less heat loss than would occur with a straight wire filament. In some lamps the coiled filament is again coiled on itself, resulting in a further reduction of heat loss and therefore giving still higher efficiency in terms of light output for a given expenditure of power in the lamp. Tungsten is widely used for the filaments of modern lamps, and the operating temperature is usually in the region of 3,000 degrees Centigrade.

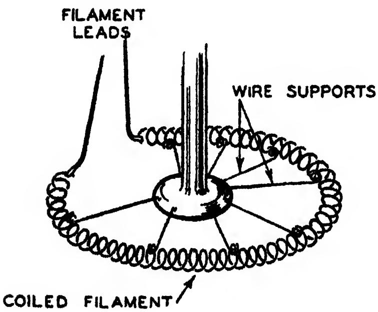


Fig. 8.—Arrangement of Coiled Filament in Gas-Filled Lamp.

Several forms of filament lamps are available for special purposes, such as use in projectors, where small size and concentration of the filament are usually necessary so as to obtain a concentrated light beam.

Arc Lamps

An arc between carbon electrodes in air forms a high intensity source of light, most of which comes from the tip of the positive carbon where temperatures up to about 4,000 degrees Centigrade are reached. Either A.C. or D.C. may be used, but with A.C. a crater forms in both electrodes whereas with D.C. there is a crater only on the positive electrode. As the crater is the source of brightness, the D.C. arc is preferable for

projection work and in searchlights, etc., where the light has to be focused.

As the carbons burn away during use, the arc distance must be continuously adjusted. It is not always convenient for this to be done manually, and automatic methods have been developed in which the correct distance between the carbons is maintained by a solenoid operating from the voltage across the arc itself. As the arc gap lengthens the voltage rises, causing the solenoid to feed the carbons together again until the original conditions are restored. The arc voltage varies, according to the conditions, between about 30 and 100 volts.

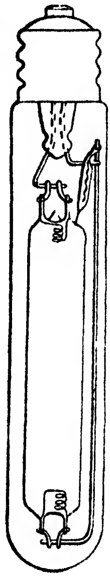


FIG. 9. MERCURY VAPOUR DISCHARGE LAMP.

Discharge Lamps

A variety of luminous effects may be obtained by passing current through different gases, each gas giving light of a particular colour under these conditions. The effect has been used in practice, in the development of discharge lamps, which are mainly used for the illumination of large areas, as in street lighting and large factory premises.

One form of discharge lamp which uses mercury vapour is shown in Fig. 9. There are two independent tubular glass bulbs, the inner one being provided with main electrodes at each end between which the main discharge takes place. An auxiliary or starting electrode, situated near one of the main electrodes and connected to the opposite pole of the supply, serves to start the discharge. The space between the inner and outer bulbs is evacuated so as to ensure an even temperature of the inner bulb, which contains a little mercury and some argon gas at low pressure. When the lamp is switched on, full voltage is applied between the starting electrode and the corresponding main electrode, with the result that a discharge is started between them through the argon gas. The heat of this discharge vapourizes the mercury, and the discharge through the mercury vapour between the two main electrodes then takes place.

Lamps of this kind give two or three times as much light as the filament type for a given power input, but their control circuits are fairly complicated.

Fluorescent Lamps

A considerable part of the energy radiated by a mercury vapour lamp belongs to the invisible part of the spectrum, i.e. it cannot be seen, and is, therefore, not useful for illumination purposes. To overcome this defect, the fluorescent type of discharge lamp has been developed, making use of the property possessed by certain substances of emitting visible light when acted upon by invisible radiation from the ultra-violet part of the spectrum. In this way, the energy which would otherwise be wasted is converted into useful illumination.

Each fluorescent material produces light of a particular colour, as shown below :—

Cadmium phosphate.. ..	Red.
Calcium tungstate	Blue.
Magnesium tungstate ..	Bluish-white.
Zinc beryllium silicate ..	Orange or yellow.
Zinc silicate	Green.

By suitably mixing these materials it is possible to obtain almost any colour, including that of daylight. In the fluorescent type of discharge tube, the fluorescent powders are deposited on the inside walls and become excited so as to emit light of their particular colour when the tube is in operation. As the powders lose their efficiency at high temperatures, fluorescent lamp tubes are usually made larger in diameter than those of ordinary discharge lamps to provide a greater cooling surface.

ELECTRIC POWER

There are many ways in which electricity may be used to produce mechanical power, the principal method being by means of electric motors. These machines are made in a wide variety of forms for A.C. or D.C. operation with different properties to suit particular applications, but in all cases their operation depends upon the principles of electromagnetism relating to the production of magnetic fields by electric currents and the forces which exist when these fields and currents react upon each other.

Magnetic Effects of Currents

When a current flows through a conductor the neighbourhood of the conductor is occupied by a magnetic field, the direction of which at any point can be found by means of a compass

needle. Experiment shows that in the region of a straight wire carrying a current, the lines of force of the field representing its direction form a series of circles with their plane at right-angles to the wire as shown in Fig. 10. The magnetic field is strongest close to the wire and its strength decreases rapidly as the distance from the wire increases.

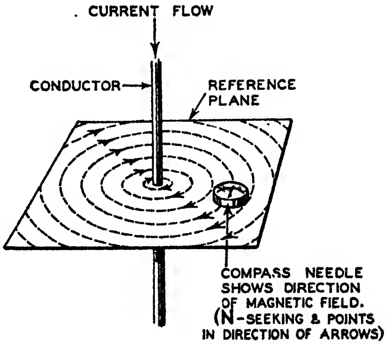


Fig. 10.—Magnetic Field Produced by a Wire Carrying Current.

There is a definite relationship between the direction of the lines of force and the direction of the current To an observer looking in the direction of the current, the field circles are in a clockwise direction and it follows that when viewed from the opposite side the direction is anti-clockwise. It is important to realize that the field circles do not rotate; they simply show the direction of the field, as would be indicated by a small compass needle placed in various positions near the conductor. The relationship between the directions of current and field is the same as that applying to the direction in which a corkscrew moves when rotated.

Some important effects occur when two wires carrying current are placed close to each other. There are two conditions, according to whether the currents are flowing in the same or in opposite directions, as shown respectively at (a) and (b) in Fig. 11. With both currents in the same direction the fields

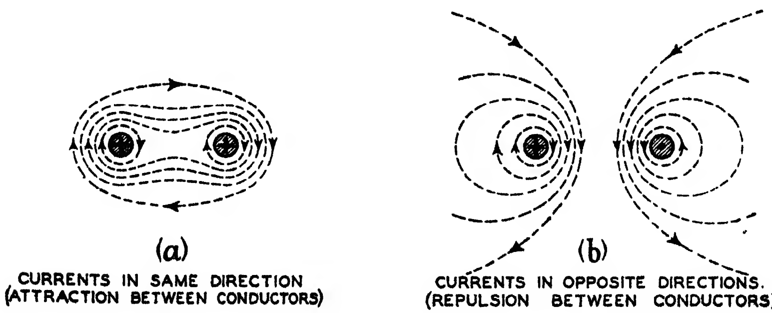


Fig. 11.—Interactions of Magnetic Fields Between Adjacent Conductors.

around the respective wires add together, giving a linking effect which tends to pull the conductors together. With currents flowing in opposite directions, the respective fields are opposed and there is a force of repulsion tending to separate the conductors. The forces produced are greater with high currents and short distances, and have to be allowed for, in practice, in the design of apparatus where cables or conductors carrying heavy currents are run side by side. In cases where abnormally high currents can flow under fault conditions, it is possible for very great forces to be exerted between the conductors, with considerable risk of damage to supporting structures and distortion of the conductors themselves.

The Solenoid

If a wire is wound into the form of a helix or long coil, as shown in Fig. 12, the magnetic fields of the individual wires will combine to produce a resultant field passing through the inside of the coil in the direction of its length and completing the magnetic circuit in the region outside. Such an arrangement is called a solenoid, and is widely used in practice.

It will be seen that the resultant field is in a particular direction determined by the directions of the fields due to each wire. The drawing in Fig. 12 represents a section through the field in a plane passing down the axis of the coil. With the current in the direction shown, the left-hand end of the coil is of North polarity. Reversal of current gives a reversal of polarity. While

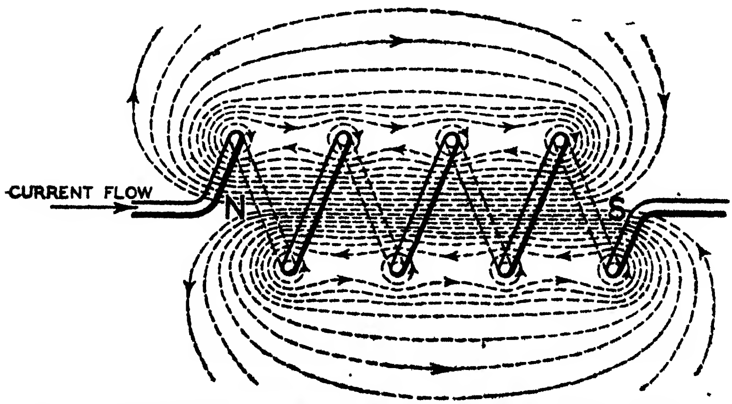


Fig. 12.—Relation Between Direction of Current and Field in Simple Solenoid.

the current flow is maintained, the coil produces a magnetic field and can be used in the same way as an ordinary magnet. The arrangement represents one form of *electromagnet* and has the advantage over a permanent magnet that by varying the current strength, the strength of the magnetic field is also varied.

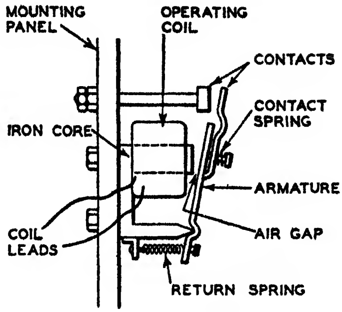


FIG. 13.—ELECTROMAGNETIC RELAY.

One of the many applications of electromagnets is represented by the type of relay shown in Fig. 13. In this case, the coil is wound in several layers and has an iron core which forms part of the magnetic circuit. This circuit is completed by an iron armature carrying the moving contacts, and by the air gap which separates the armature from the projecting end of the core, called the pole face, when the relay is open. If a suitable voltage is applied to the coil leads, a magnetic field is established through the core and armature and across the air gap. The resulting attraction of the armature causes the contacts to come together, thus closing any circuit connected to them. When the operating coil is switched off the magnetic field collapses, releasing the armature, and the contacts open. By this means, it is possible to control the opening and closing of circuits from a distant point. The controlled power is generally very much greater than that required to operate the relay.

The Motor Principle

Some very important effects take place when a conductor carrying a current is placed in a magnetic field. We have already seen that such a conductor will be surrounded by its own magnetic field and that magnetic fields react upon each other so as to produce forces. In Fig. 14, (*a*) represents a conductor carrying current and with its accompanying magnetic field. A uniform field between two magnetic poles is shown at (*b*), while (*c*) shows what happens when the conductor is placed in the field. With the current flowing in the direction shown, away from the observer, the field on the right-hand side of the conductor is in the same direction as the field at (*b*), so that

when the conductor is placed in the field there will be a concentration of field on the right-hand side of it, where the fields add, or assist each other, and a weakening of the field on the left-hand side owing to the opposition of the respective fields on this side, as shown at (*c*). The result of this distortion is a force on the conductor tending to displace it to the left, as if the stretched lines of force were elastic bands.

If the direction of the field or of the current flow is reversed, the direction of the force is reversed, but if both field and current are reversed the direction of the force remains unchanged. These relationships are summed up by Fleming's *Left Hand*

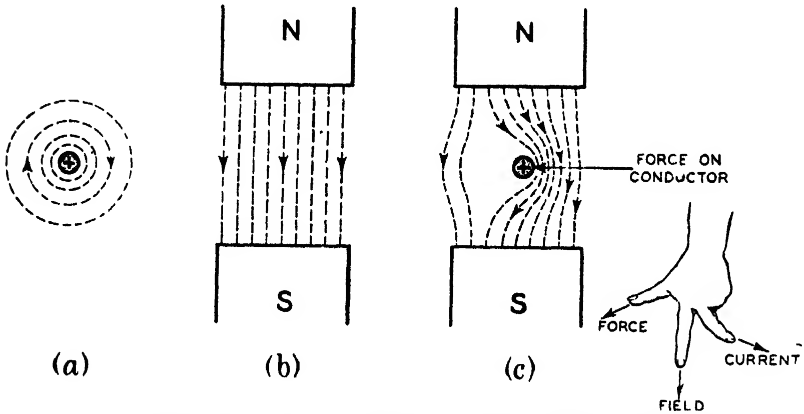


FIG. 14.—SHOWING EFFECT OF PLACING CURRENT-CARRYING CONDUCTOR IN UNIFORM MAGNETIC FIELD.

Rule, which states that if the thumb and first and second fingers of the left hand are held at right-angles to each other, the first (index) finger pointing in the direction of the field (i.e. from North to South poles) and the second finger in the direction of the current, then the thumb will indicate the direction of the resulting force, as shown in the diagram adjacent to Fig. 14(*c*).

The production of mechanical force in this way is the basis of operation of the D.C. motor, which produces rotary force, or torque, as long as current is supplied to it.

The D.C. Motor

The basic form of D.C. motor is shown in Fig. 15, representing a single loop of wire mounted on a central shaft and free to rotate in the magnetic field between the poles N and S

The ends of the loop are connected to the two halves of a rotary change-over switch, called a commutator, which is fixed to the shaft and has bearing upon it two contact strips or brushes, by means of which current can be conveyed to the loop. The field in which the loop is located can be produced either by permanent magnets or electromagnets; the latter being more usual in practice.

It can be seen that with the arrangement shown, current can flow in at one brush, traverse the loop and pass out through the other brush. Owing to the commutator being in two halves, however, a special condition arises when the slots or gaps between the commutator segments pass under the brushes, which happens when the loop is vertical. At these times, twice in each revolution, the loop will be either short-circuited by the brushes or open-circuited, according to whether the commutator gaps are narrow or wide, and the arrangement of the brushes. In either case, the current flow in the coil is interrupted at these particular points of rotation.

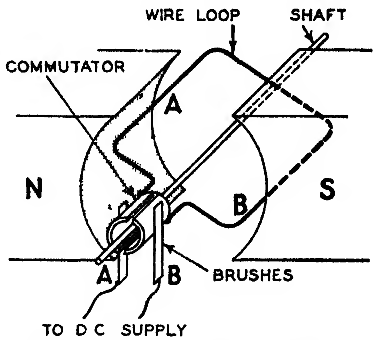


FIG. 15—BASIC FORM OF D.C. MOTOR

It may also be noticed that if, for example, brush A is positive, then coil-side A will carry a current away from the observer while it occupies a position under the N-pole as shown in the figure, but when it passes through the vertical position and comes under the S-pole its corresponding commutator segment becomes negative under brush B and the current flow is then towards the observer. Similar changes occur in coil-side B, giving a reversal of current through the loop each time the coil-sides pass from the region of one pole to the next.

The way in which this elementary form of motor is able to produce power may be understood from Fig. 16, representing sectional views looking along the shaft. In diagram (a), coil-side A is connected to the positive brush through the commutator and therefore carries the current away from the observer, while in coil-side B the current flow is towards the observer. The directions of the fields produced by these currents are shown by the arrows encircling the respective coil-sides, being

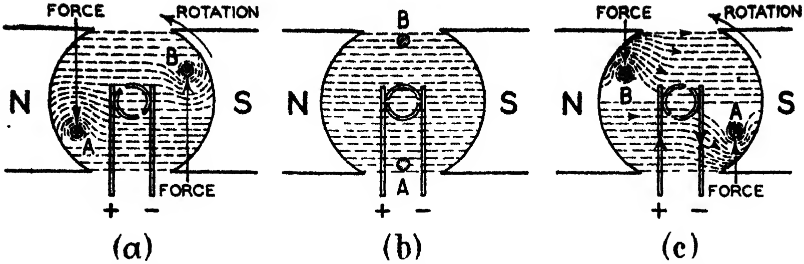


FIG. 16.—SHOWING HOW THE ROTATION OF A D.C. MOTOR IS PRODUCED.

clockwise for A and anti-clockwise for B. The reaction of these fields with the main field produces distortion and a piling-up of lines of force on one side of each coil-side as shown. As already explained, this effect gives a force on each coil-side as indicated by the straight arrows. These forces act together so as to turn the coil around its axis in an anti-clockwise direction. As this turning motion continues, the plane of the coil becomes vertical, as shown at (b). The coil is now short-circuited through the commutator segments and brushes and there is no turning force.

This position is therefore a dead-spot, and represents one reason why this elementary form of motor would not be satisfactory in practice. If the coil is freely mounted, however, its momentum will carry it on in the same direction, bringing coil-side A under the S-pole. At the same time, the action of the commutator changes the direction of current flow in the coil. This means that although the respective coil-sides are now under different magnetic poles, as compared with diagram (a), the conditions of current flow are the same, and the forces on the coil continue to be exerted in the same direction.

So long as the direction of the main field and of the current supplied to the brushes is unchanged, the motor will continue to run in the same direction. If the field is reversed, or the polarity of the brushes changed, the direction of rotation will be reversed. If *both* these changes are made, however, the direction of rotation will be the same, because under these conditions the reactions between the main and coil fields will result in a building-up of lines of force on the same side of each conductor as before. Application of the Left Hand Rule will also show that if the directions of field and current are reversed the force still acts in the same direction.

General Arrangement of D.C. Motor

Practical forms of D.C. motor employ electromagnets for the field system, and in place of the single rotating loop of wire there is an *armature,* consisting of an iron drum slightly smaller in diameter than the bore of the field pole-pieces and having embedded in slots around its outside edge, a large number of conductors connected to a multi-segment commutator. There are numerous types of armature windings, but in all cases the effect obtained is a magnification of the torque or turning force produced by a single conductor and a uniform torque at all points of rotation.

The effect of the iron in the armature is to concentrate the magnetic field and to make its strength much greater than would be the case without it, owing to the fact that the field passes much more readily through iron than air. Owing to the production of eddy currents causing wasteful heating when a conducting body rotates in a magnetic field, the armature is built up from thin iron laminations having their plane in line with the lines of force, i.e. at right-angles to the shaft. This practice is universal in all types of electrical machines, including generators (see page 43) and reduces the heating from eddy

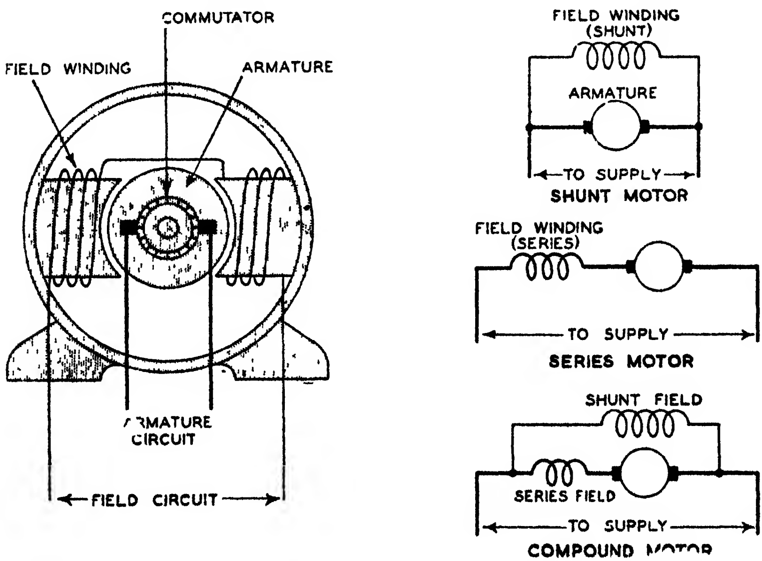


FIG. 17.—GENERAL ARRANGEMENT AND METHODS OF CONNECTING A D.C. MOTOR.

currents by confining them to thin laminations of high resistance instead of the low resistance represented by a large solid body.

The general arrangement of a D.C. motor is shown in Fig. 17. In practice there may be more than one pair of field poles, especially in large machines, which may have twelve or more poles. There are several ways in which the field and armature windings may be connected, according to the intended application of the motor, the chief methods being the same as for D.C. generators (see Fig. 14, page 48). The respective arrangements are shown diagrammatically in Fig. 17.

The Shunt Motor

In the case of the shunt motor there is one field winding on each pole, these windings being connected in series across the supply. The field strength, which is dependent upon the current in the field windings, therefore depends upon the supply voltage and is independent of the armature current (i.e. the load on the motor) except for the distortion caused by the reaction of the armature field.

Back-e.m.f.

In all D.C. motors, the rotation of the armature conductors in the main field causes the production of a voltage in accordance with the principles of the generator as described in Chapter II (see page 42). Application of the *Right* Hand Rule to Fig. 16, for example, will show that this voltage due to rotation, or back-e.m.f. as it is called, tends to drive the armature current in the opposite way to the direction in which it is supplied. The effect of the back-e.m.f. is, therefore, to reduce the current flowing in the armature circuit and to establish a balance with the applied voltage. When the armature is at rest there is, of course, no back-e.m.f., and as the armature current in this case is limited only by the resistance of the armature winding, it is usually necessary to insert extra resistance in the armature circuit at starting in order to limit the current to a safe value.

When the armature begins to rotate, there is a small back-e.m.f., which rises as the speed increases. All this time the armature is producing the torque, or turning effort, needed to accelerate the load, and in doing so takes a current which is

always proportional to the load. This still applies when the armature has reached full speed, representing a state of balance in which the current flowing in the armature is sufficient to produce the required torque to drive the load. The back-e.m.f. is less than the supply voltage by the amount necessary to send the required current through the armature.

If the load on the motor is changed, this state of balance is upset. An increase of load means that more torque is required and more armature current must flow. In order to produce this increase, the armature must slow down, so as to make a larger difference between the supply voltage and the back-e.m.f. If the load is decreased, less torque is required, the current falls, and the speed increases, giving a smaller difference between supply voltage and back-e.m.f.

Speed Control of Shunt Motor

As the back-e.m.f. at a given speed is proportional to the field strength, just as in the case of a generator, a change of field strength will cause a change of back-e.m.f. and therefore a change of speed in order to restore the conditions of voltage balance determined by the load. In the case of the shunt motor (Fig. 17), the field can be weakened by inserting resistance in the field circuit and this provides a means of obtaining speed control above the normal speed of the motor. The normal speed may be reduced by inserting resistance in the armature circuit. The flow of armature current through this resistance causes a voltage drop and this reduces the voltage applied to the armature circuit. To meet this condition, the armature slows down, because less back-e.m.f. is required to balance the applied voltage.

The connections of a shunt motor arranged for speed control by shunt and series regulation are given in Fig. 18. It may be pointed out that as resistance is normallly required in the armature circuit for starting purposes, the function of a starting and series regulating resistance may be combined, provided that it is suitably rated to carry the armature current continuously. The lowest speed is obtained with all the armature resistance in circuit and all the field resistance cut out. The highest speed is obtained with all the field resistance in circuit and all the armature resistance cut out.

The speed of the shunt motor falls slightly as the load increases,

owing to the increased voltage drop in the armature due to the increased current. A lower value of back-e.m.f. is required to balance the supply voltage under these conditions, and the armature accordingly slows down.

The shunt motor is widely used, in practice, for drives where the speed must remain fairly constant under changing load and

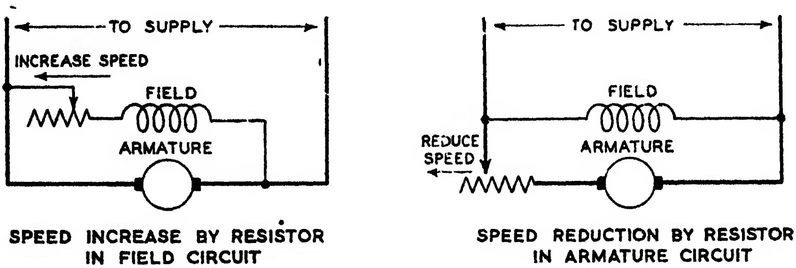


Fig. 18.—Speed Control of Shunt Motor.

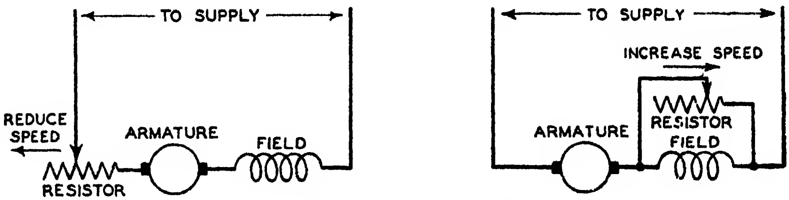
also where speed control, above or below normal, may be required without undue complication.

The Series Motor

The distinctive feature of the series motor is that the field coils must be wound with sufficiently large wire to carry the armature current. There is one field coil on each pole, the coils being connected in series with each other and with the armature.

The field strength of the series motor is dependent upon the armature current (unlike the shunt motor), so that at light loads the field is correspondingly weakened and the speed rises appreciably. Conversely, an increase of load strengthens the field and the speed falls. The speed may be reduced below normal by inserting resistance in the armature circuit. It must be noticed, however, that a reduction of load, and therefore of armature current, is accompanied by a weakening of the field so that if the torque and current fall with a reduction of speed, as is usually the case, the effect of armature resistance tends to be offset by the weakening of the field. Thus a relatively high series resistance is required to obtain a given speed reduction as compared with the shunt motor, in which the field strength remains approximately constant.

Speed increase above normal speed may be obtained, as shown in Fig. 19, by shunting the series field by means of resistance connected in parallel with it. This has the effect of shunting some of the current through the resistance and, therefore, of weakening the field. Low values of resistance give the greatest shunting effect and therefore the greatest speed increase.



SPEED REDUCTION BY RESISTOR IN ARMATURE CIRCUIT

SPEED INCREASE BY FIELD-SHUNTING RESISTOR

FIG. 19.—SPEED CONTROL OF SERIES MOTOR.

An important feature of the series motor is that at starting, a high current results in a correspondingly strong field, enabling the armature to produce a high starting torque.

The Compound Motor

The features of the shunt and series type of motor may be combined in one machine by providing both series and shunt windings for the field. This arrangement gives the compound motor. There are two windings on each field pole; a heavy or series winding for carrying the armature current, and a shunt winding connected to the supply, the connections being as shown in Fig. 17. Each winding is formed by the series connection of the corresponding coils, and the fields due to the respective windings aid each other.

Speed control of a compound motor above or below normal speed may be obtained respectively by means of resistance in the field or armature circuit, as in the case of the shunt motor (Fig. 18).

The compound motor may be regarded as having a higher starting torque than a shunt motor and a more constant speed under changing load conditions than the series motor. Either feature may be emphasized by varying the proportion of the total field strength due to each winding. A relatively strong

series winding will make the motor approach more nearly to a series motor in its operation, and the chief function of the shunt winding will be to stabilize the speed somewhat under changing load conditions. If the shunt winding predominates, the chief effect of the series winding will be to enable the motor to exert a greater starting torque than could be produced by a corresponding shunt motor.

Starting of D.C. Motors

The armature of a D.C. motor a has relatively low resistance, so that an unduly high current would be drawn from the supply if the machine were switched on without any form of current limitation. It is sometimes permissible to start small motors by direct switching to the supply, provided that they are designed to withstand these conditions and that other circuits are not upset by the high starting current, but in most cases some form of starter is used. This consists essentially of a resistance connected in the armature circuit and arranged for short-circuiting in sections, one after another, as the motor gains speed. This action may be either manual, as by moving a contact arm over a series of field contacts between which the sections of resistance are connected, or automatic, in which the starter may be remote controlled by means of start and stop push-buttons.

A simplified diagram of one form of automatic starter is given in Fig. 20. The starting resistance is connected in sections R1, R2, etc., between the fixed contacts and in series with the motor armature as shown. A set of moving contacts carried on a rotatable support is arranged with the contact fingers staggered behind each other so that they close on the fixed contacts in the order 1, 2, 3, 4, when the contact support is pushed upwards. This motion is provided by a solenoid, which is connected to the supply when the start push-button is pressed. The motion is retarded by a device working on the pump principle so that sufficient time is allowed on each step for the motor to reach the corresponding speed. An adjustment is usually provided so that the starting time may be varied to suit individual starting conditions. It will be noted that the shunt field of the motor is connected so as to receive the full supply voltage at all times, thus ensuring full field conditions and an adequate starting torque from the motor. The retarding device delays only the closing action, and releases immediately, so as to insert all the

starting resistance and open the motor circuit, including the field, as soon as the stop push-button is pressed.

There are, of course, many variations in the form of starting apparatus, according to the size of the motor and the operating conditions. Protective devices must also be included to safeguard the motor under conditions of overload and to ensure that

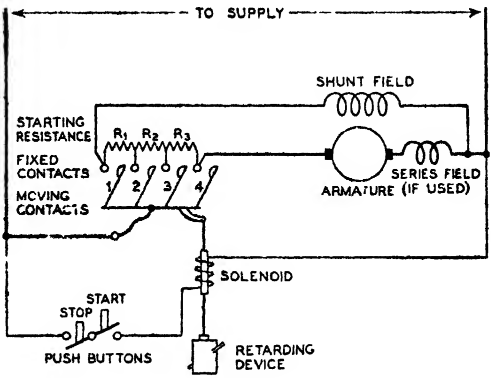


FIG. 20.—CONNECTIONS OF SIMPLE AUTOMATIC STARTER.

The moving contacts are operated by a solenoid which is connected to the supply when the start push-button is pressed and the closing action is delayed by the retarding device.

it does not restart unexpectedly upon resumption of the supply after a voltage failure.

A.C. Motors

An alternating current, or voltage, as the name implies, varies continuously in value and in direction, rising to a maximum, falling again through zero and rising to a maximum in the opposite direction; this process going on for as long as the circuit remains closed. In commercial power supply systems there are 50 complete cycles of reversal per second, each cycle being represented by the sequence: zero—maximum (positive)—zero—maximum (negative)—zero. The number of cycles per second is called the frequency of the supply, and may theoretically have any desired value, although 50 cycles is the frequency standardized for industrial supplies. The production of an A.C. supply by means of alternators was described in Chapter II, where the treatment referred to single-phase systems, in which only one voltage and a corresponding current flowed in the circuit. In practice, considerable use is made of multi-phase systems, where two or more voltages are applied in a particular way so that their effects supplement each other. Supplies of

this kind are produced by alternators having two or more sets of windings, or phases, a three-phase arrangement being now practically universal for industrial purposes.

The diagrams in Fig. 21 show how the voltages vary in single, two- and three-phase systems. In each case the horizontal line represents zero voltage and the duration of a complete cycle is 360 degrees, corresponding to one-fiftieth of a second in the case of a 50 cycle supply. In a two-phase supply the voltages are 90 degrees, or a quarter of a cycle, out of phase, which means that in one phase the voltage is passing through its maximum while the voltage in the second phase is zero. In the three-phase case, the voltages are 120 degrees out of phase with each other, so that the phase difference is a third of a cycle. In applying these voltages to motors, the object is to make each phase of the two- and three-phase supplies contribute to the total power output. The single-phase case is rather special, and is dealt with separately.

The Rotating Field

In a particular class of A.C. motors known as induction motors, rotation of the moving member, called the rotor, is obtained by producing in the stationary member, called the stator, a magnetic field which revolves at a speed depending on the frequency of the supply and the number of pairs of stator poles. The magnetic circuits of both stator and rotor are laminated, so as to minimise the heating effect of eddy currents, and the windings on each member are distributed in slots in the laminations instead of the field member having projecting poles.

Two different forms of rotor winding may be used with induction motors. One of these, represented by the squirrel-cage rotor, has a winding short-circuited on itself without any external connections. The other type, known as a slip-ring rotor, has a three-phase winding with connections brought out to three slip-rings. The object of this arrangement is to allow the connection of starting resistance in the rotor circuit; this resistance being cut out in steps as the motor speeds up. Resistance connected in this way may also be used as a means of speed control, the effect of added resistance in the rotor circuit being to reduce the speed of the motor. Apart from the question of speed control, the slip-ring motor has advantages over the squirrel-cage type in the matter of starting properties, as the

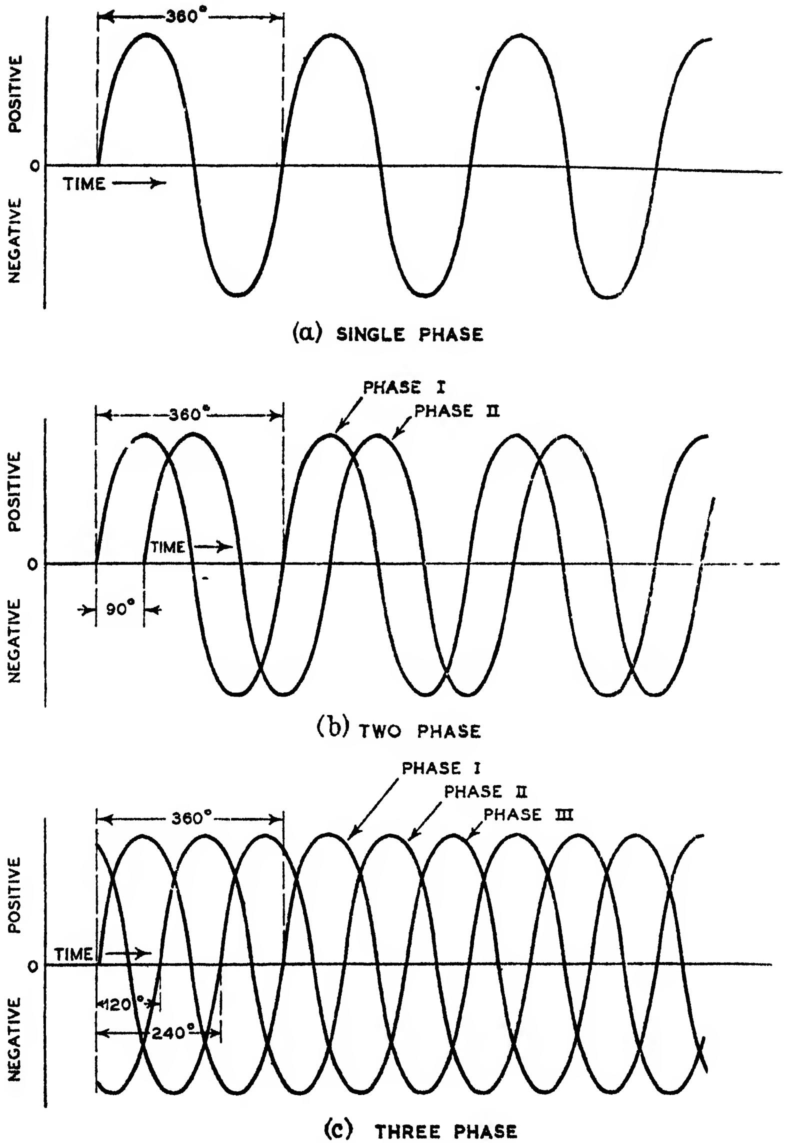


FIG. 21.—RELATIONSHIP BETWEEN VOLTAGES IN 1-, 2- and 3-PHASE SYSTEMS.

torque during starting can be made higher by the added resistance without reducing the efficiency during running or making the motor run at a slow speed because of the high fixed value of rotor resistance.

The way in which a rotating field is produced in the stator of an induction motor is shown in Fig. 22. The stator is shown with projecting field poles for simplicity, and it is seen that each phase of the supply is used to energize one pair of poles. The motor is thus a two-pole machine, and not six-pole, there being only two poles per phase. Diagram (a) shows how each pair of poles is connected so that when current flows through that particular phase in either direction the poles facing each other are always of opposite sign. The phase relationships between

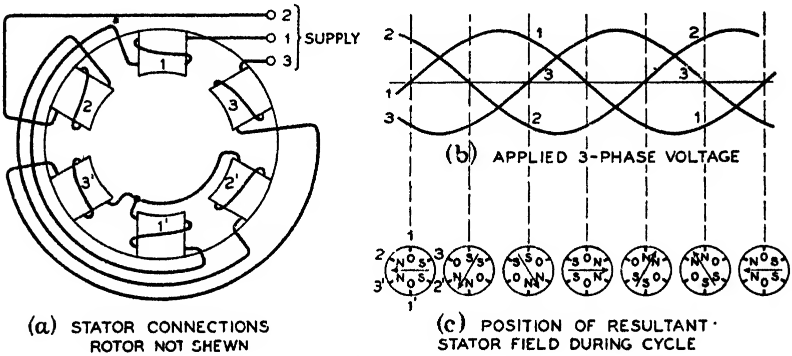


FIG. 22.—PRODUCTION OF ROTATING FIELD FROM 3-PHASE SUPPPLY.

the respective phase voltages are shown in diagram (b). The sequence of drawings at (c) shows how the direction of the resultant field in the stator changes throughout a complete cycle of applied voltage.

At the instant corresponding to the first zero of phase 1, the poles 1, 1^1 will have no field, and are consequently marked 0 in the first diagram of sequence (c). At the same instant, phase 2 is positive, making poles 2 and 2^1 North and South respectively. Phase 3 is equal and opposite to phase 2, making poles 3 and 3^1 South and North respectively. This arrangement of polarities, shown in the first diagram of sequence (c), gives a resultant field directed as shown by the arrow. At the next moment considered, corresponding to zero of phase 2 voltage, poles 2 and 2^1 will have no field while poles 1, 1^1 become S and

N, respectively and poles 3, 3^1 are also S and N, respectively. With this array of poles, the resultant field occupies the position shown in the second diagram of sequence (c). The same reasoning may be applied throughout the figure, showing that for each position considered, the direction of the resultant field moves the same amount (60 degrees or one-sixth of a cycle) in the same direction. The first and last diagrams in sequence (c) represent the same conditions.

It will be understood that the field does not move round in a sequence of jerks. The diagrams merely show how continuous rotation is obtained by considering the position of the field at equally spaced but isolated moments. At intermediate moments, the resultant field has different directions because of the variation in the relative strengths of the respective poles, as determined by the relative values of the phase voltages. At any instant throughout the cycle, the position of the resultant field is determined by these phase relationships and the field sweeps round the stator at a perfectly constant rate.

Speed of Rotating Field

In the case of a two-pole machine, as shown in Fig. 22, the field completes one revolution during one cycle of the supply. This means that with a 50-cycle supply the field would rotate 50 times per second, or 3,000 times per minute. In a four-pole motor, the distance between the poles of one phase is only half as much and with a supply of the same frequency, the speed of the field would be 1,500 revolutions per minute. In general, the speed of the field in revolutions *per second* is equal to the frequency in cycles per second divided by the number of *pairs* of poles. Thus, for a six-pole motor on a 50-cycle supply the field speed would be $16\frac{2}{3}$ revolutions per second, or 1,000 r.p.m.

The Rotor

The field speed is not the speed at which the rotor revolves in the machine. The actual rotor speed of the induction motor is always somewhat lower, as will be seen when the action of the rotor is considered. It has been pointed out that there are two different forms of rotor ; the squirrel-cage or short-circuited type and the slip-ring type. The sectional drawing in Fig. 23 shows a squirrel-cage rotor located in the stator, the end bearings

and part of the stator winding being omitted to show the construction. The rotor end-rings are generally welded or brazed to the rotor conductors, giving a very robust construction. The arrangement of a slip-ring motor is shown in Fig. 24, from which it is seen that the rotor winding is in the form of wire coils. The rotor winding is three-phase, the ends being brought to the three slip-rings so that external resistance may be connected between them for starting purposes.

Action of the Rotor

A portion of the stator and rotor of an induction motor is shown in Fig. 25. It is assumed that the stator field which, of course, also links the rotor conductors, is rotating in an anti-clockwise direction. This is the same thing, so far as the rotor conductors are concerned, as a clockwise rotation of these conductors through a stationary field. Application of the Right

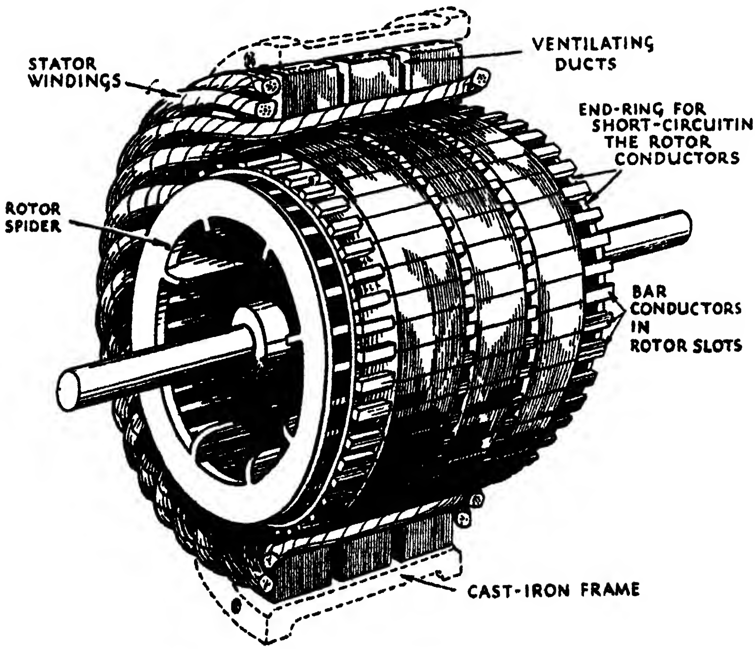


FIG. 23.—ARRANGEMENT OF SQUIRREL-CAGE INDUCTION MOTOR.

In this motor, the rotor bars and end-rings are of copper. The joints between bars and end-rings are usually made by welding.

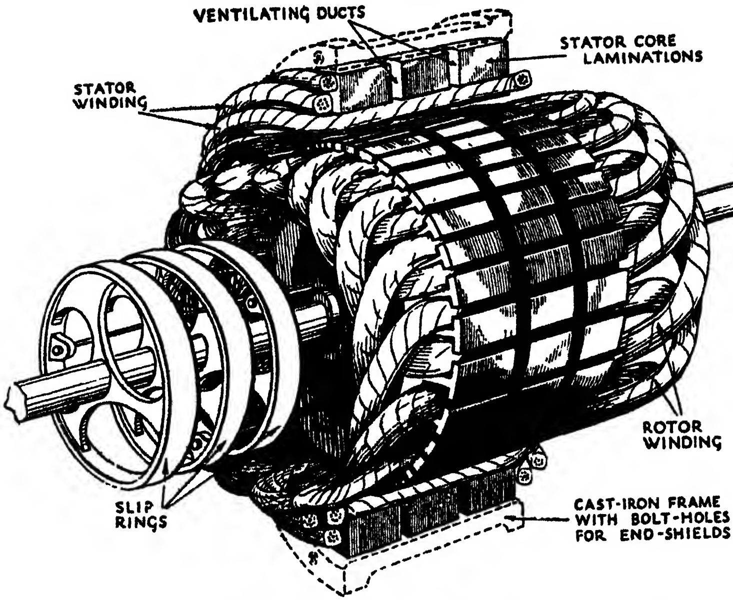


FIG. 24.—ARRANGEMENT OF SLIP-RING INDUCTION MOTOR.
Notice the manner in which the end connections of the rotor winding are arranged so as to be self-supporting.

Hand Rule will show that the currents induced in the rotor conductors by their movement relative to the field will be away from the observer, as indicated by the crosses inside each conductor.

The fields resulting from these rotor currents produce distortion of the field as shown, and from application of the Left Hand Rule it can be seen that the field reactions cause a force or torque on the rotor conductors tending to displace them to the left, i.e. in the same direction as the stator field. The rotor is therefore urged to follow the stator field, but cannot reach the same speed. If it did, there would be no relative movement between stator field and rotor conductors, no induced rotor current, and therefore no torque to drive the rotor. The rotor speed is always a few per cent. less than the field speed ; the difference of speed, or *slip* as it is called, being sufficient to produce in the rotor conductors enough current to provide the torque required to drive the mechanical load. An increase of load is, therefore, accompanied by a drop in speed (increased slip) and *vice versa.*

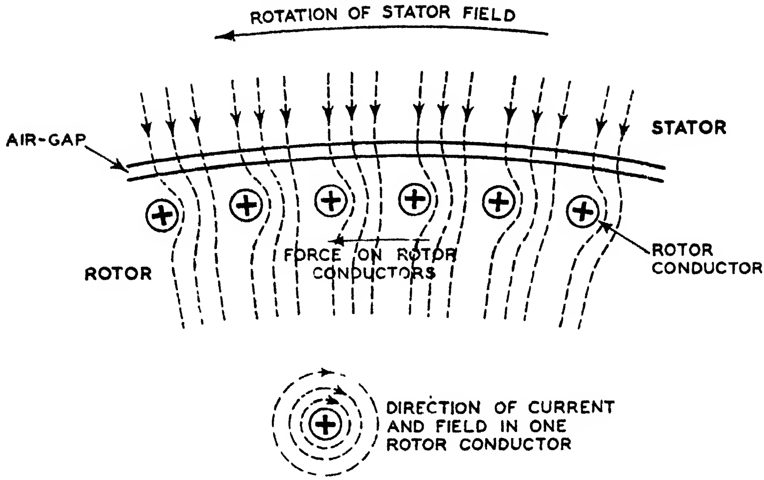


FIG. 25.—PRODUCTION OF TORQUE IN ROTOR OF INDUCTION MOTOR.

Two-phase Motors

The principles applying to the operation of induction motors from a two-phase supply are similar to the three-phase case, except that the stator has two sets of windings (phases) instead of three. The two phases combine to produce a rotating field in the stator, and the rotor may be either squirrel-cage or slip-ring. Owing to the greatly restricted use of two-phase supplies, this type of motor is not now of much practical importance.

The Single-phase Induction Motor

A single-phase supply may be used to produce a rotating field if a second or auxiliary phase is introduced on the stator in such a way that a two-phase field system is created. To obtain this effect, it is necessary for the voltage and current in the auxiliary phase to vary in the proper time relationship with respect to the main phase, giving the kind of conditions applying in a two-phase circuit (Fig. 21(b)). This result is obtained by connecting capacitance or inductance in series with the auxiliary winding, but there are several ways of arranging the circuit.

A typical arrangement is shown in Fig. 26. To start the motor, the running winding is connected to the supply and the starting switch is then closed. This connects the auxiliary or

starting winding to the supply in series with the condenser. The capacitance, introduced in this way, alters the phase position of the current and the field in the auxiliary winding relative to the main field, and gives the conditions necessary for producing a rotating field in the stator. This field acts upon the rotor, which may be a squirrel-cage or slip-ring, as already explained, and the motor runs up to speed under the conditions created artificially by the auxiliary phase. When full speed is reached, the starting switch is opened, disconnecting the auxiliary winding and condenser. The motor continues to run normally because the stator and rotor fields combine to produce conditions resembling those of a rotating field, although the motor has a relatively small power output in comparison with a two- or three-phase machine of equivalent size.

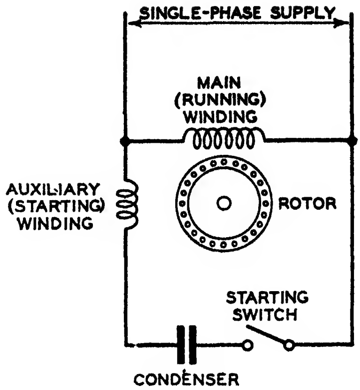


FIG. 26.—CONNECTIONS FOR SPLIT-PHASE STARTING OF SINGLE-PHASE INDUCTION MOTOR.

In some cases, the motor is designed to run continuously with the auxiliary winding and condenser in circuit. Motors operated in this way are much more efficient than those in which the starting winding is disconnected when the machine has accelerated.

The Shaded-pole Motor

A further principle of operation which can be used to make a single-phase motor self-starting is represented by so-called shaded poles. These are portions of the main poles encircled by a short-circuited coil or winding, the arrangement being virtually another way of obtaining an auxiliary field which combines with the main field to produce a rotating field in the stator.

The arrangement of the field poles is shown in Fig. 27. The rotor is generally of simple squirrel-cage form, and machines of this type are made only in small sizes because of their low starting torque and poor efficiency. They are quite suitable

for driving light mechanisms where self-starting from a single-phase supply is necessary.

In operation, the field set up by the main poles links with the shading coils, producing in them a current which alternates at the same frequency as the supply. This current produces in the enclosed or shaded portion of the field poles a second field of the same frequency, but owing to the way in which the secondary field is produced it is out of phase with the main field, i.e. the points of zero and maximum do not coincide. The actual conditions are usually a very rough approximation to a two-phase field and a rotating stator field is accordingly produced.

Synchronous Motors

There is a further class of motors employing a rotating field but operating without slip, i.e. with the rotor revolving at the same speed as the stator field. This type of machine may be regarded as an inverted alternator, with alternating current supplied to it and producing mechanical power. The arrangement is shown in Fig. 28.

The synchronous principle is obtained by the use of a rotor having definite magnetic poles of its own which are locked into relative position with the rotating stator field when the motor is running. It follows that the rotor cannot run at any speed other than that of the stator field, and the only way to vary the speed would be to vary the supply frequency, which is rarely practicable. The obvious application of the synchronous motor is in cases where constant speed is required. In its simplest form the machine is not self-starting, and means have to be adopted for accelerating the rotor to somewhere near synchronous speed (the speed of the stator field) so that the rotor poles can pull into step with the rotating field.

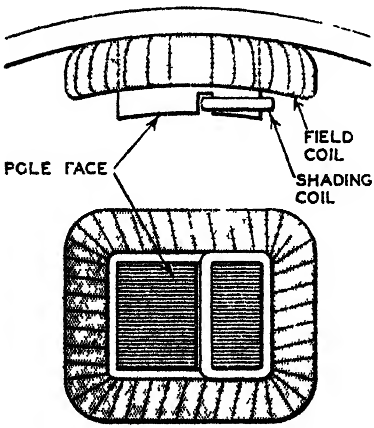


Fig. 27.—Field Pole of Shaded-Pole Motor.

There are several ways in which this can be done, depending

on the size of the motor and the starting conditions. If the starting load is very light, sufficient starting torque may be obtained from a squirrel-cage winding embedded in suitable slots in the rotor poles. When the motor has reached the maximum speed available with this winding, i.e. rather less than synchronous speed, the motor can be synchronized. Under these conditions, there is no relative movement between the squirrel-cage winding and the stator field, so that the winding becomes inoperative. An alternative method of starting employed with large motors is to use an auxiliary motor, sometimes called a " pony motor," of sufficient size to accelerate the machine to synchronous speed and usually coupled direct to the shaft. The field excitation is switched on when synchronism is reached and the synchronous motor pulls into step with the rotating field, after which the auxiliary motor is disconnected.

In a modified form of machine, known as the auto-synchronous motor, the rotor is of the ordinary slip-ring type but incorporates a D.C. generator. The motor is started as an ordinary induction motor, and is, therefore, capable of starting against load. When maximum speed is reached, the D.C. excitation is switched into the rotor circuit, producing fixed poles in the rotor winding and transforming the machine into a synchronous motor.

A.C. Commutator Motors

In dealing with D.C. motors, it was noted that changing over the armature or field connections caused reversal of the direction of rotation, whereas if both these changes were made together there was no reversal. It follows, theoretically, that a D.C. motor should run in one direction if supplied with alternating instead of

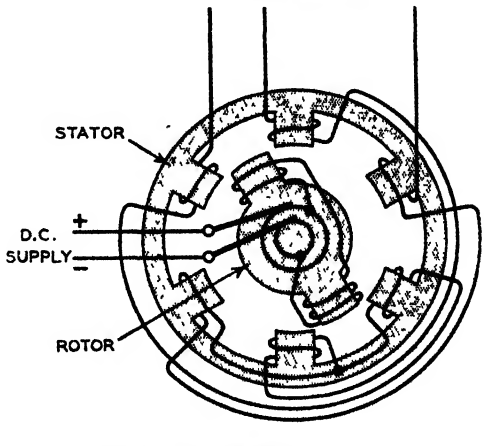


Fig. 28.—Arrangement of 3-phase Synchronous Motor (same as for 3-phase Alternator).

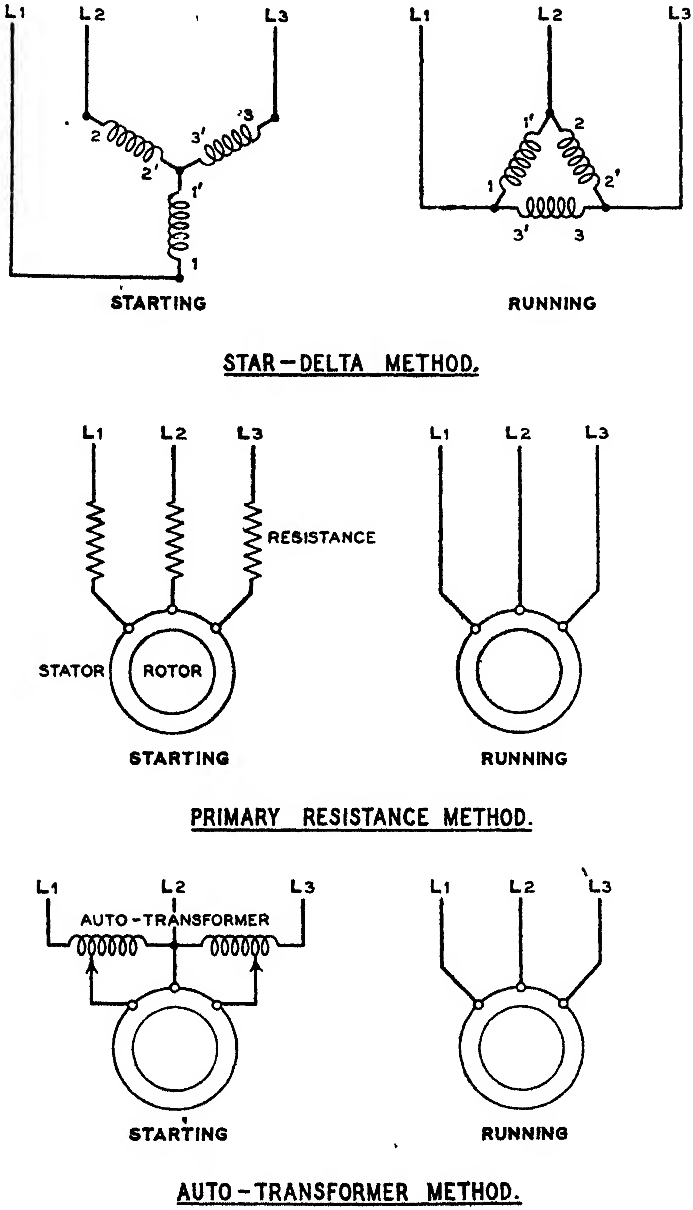


FIG. 29.—ALTERNATIVE METHODS OF STARTING 3-PHASE SQUIRREL-CAGE MOTORS.

direct current. This is true only to a very limited extent because of other factors, such as reactance, which are introduced in the A.C. case, but properly designed commutator motors resembling D.C. machines can be used successfully on A.C. supplies. The series-connected motor is best suited for A.C. working because the same current traverses both field and armature and the fields in these members are therefore reversed simultaneously with the supply alternations. For A.C. working, the field system as well as the armature must be laminated. The first successful A.C. commutator motors were series-connected machines for operating on single-phase supplies, in which service they were much more efficient than induction motors and produced a higher starting torque. As a result of extensive development, A.C. commutator motors have been produced for all classes of service and for three-phase as well as single-phase working.

Starting of A.C. Motors

Owing to the large number of types of A.C. motors there is a wide variety of starting apparatus, especially as some machines may be started in several ways.

Squirrel-cage motors generally require fairly simple starting gear and small motors can be connected direct to the supply. In cases where the starting current with this method would be excessive, some means of reducing the voltage applied to the motor at starting is adopted, the motor being allowed to accelerate under these conditions before full voltage is applied. Methods of starting three-phase motors in this way are shown in Fig. 29. In the star-delta method, the stator winding must have both ends of each phase brought out to terminals and be designed to operate with the full supply voltage across each phase (delta connection). The star grouping of the phases at starting reduces the applied voltage per phase as compared with the delta connection, thus reducing the starting current as compared with direct switching.

The remaining two methods of starting, shown in Fig. 29, do not require special motor windings, and only three stator terminals are necessary. With primary resistance starting, the starting current can be limited to the desired value to suit the conditions by choosing the appropriate resistance, bearing in mind that the starting torque will be dependent upon the current.

The auto-transformer method is relatively expensive because of the necessity for a transformer, but is efficient and used fairly extensively for large motors. The auto-transformer is a special form of transformer with only one winding instead of primary and secondary windings, the required voltage being obtained from tappings as shown (see also page 95).

In all these forms of starting, the necessary changes of connections can be made either manually, with suitable hand-operated switches, or automatically by means of electro magnetic contactors under the control of an automatic timing relay, to give

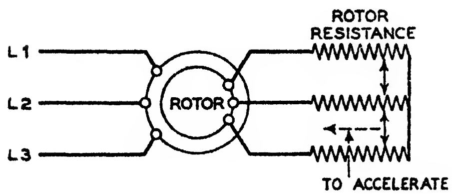


FIG. 30—METHOD OF STARTING SLIP-RING INDUCTION MOTOR.

sufficient time for the motor to accelerate before the change-over to running connections is made.

In the case of slip-ring motors, starting is effected by resistances connected in the rotor circuit as shown in Fig. 30, and cut out in steps, either manually or automatically, as the motor accelerates. If a suitable number of steps is provided, this method of starting gives gradual acceleration with relatively small starting current peaks as compared with methods where the change from starting to running conditions is made in one step.

Convertors

In practice, it is often necessary to convert from one kind of supply to another, and use is made of a D.C. motor driving an alternator or an A.C. motor driving a D.C. generator, according to the nature of the conversion required. By means of a special type of machine, called a rotary convertor, either form of conversion may be effected, thus avoiding the use of two coupled machines.

The rotary convertor has one set of field windings and an armature with a tapped winding connected to a commutator at one end and slip-rings at the other, as shown in Fig. 31. There are three ways in which the machine may be used :—

1. With commutator end supplied with D.C., machine runs as D.C. motor and A.C. may be taken from slip-ring end.
2. With slip-ring end supplied with A.C., machine runs as synchronous motor and D.C. may be taken from the commutator end.

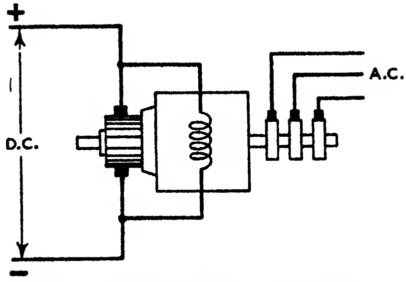


FIG. 31.—ARRANGEMENT OF ROTARY CONVERTOR.

3. If the machine is driven from an independent source of power, such as an engine, A.C. and D.C. may be obtained simultaneously. When operated in this way the machine is sometimes called a double-current generator.

Boosters

It is sometimes found that, owing to the voltage drop in a long transmission line for example, the voltage available is insufficient, and has to be augmented in some way. In such cases use can be made of a booster, representing a special form of motor-generator. The generator is series-connected in one supply line, as shown in Fig. 32, and direct coupled to the driving motor. The generator voltage, which adds to the supply voltage when the polarities are as shown, is proportional to the field strength, which in turn depends upon the load current, so that the voltage drop due to increase of load

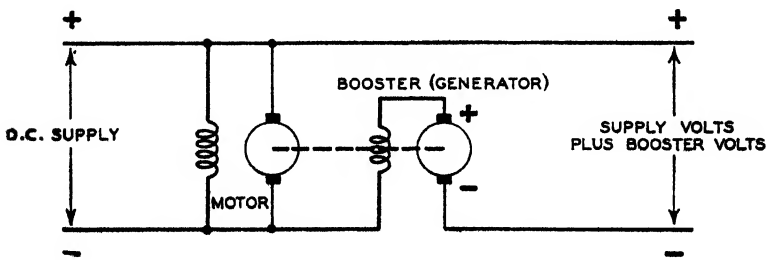


FIG. 32.—CONNECTIONS OF SERIES BOOSTER.

current is automatically compensated. By reversing the polarity of the booster, its output voltage is made to oppose the supply voltage, so that the load voltage is reduced by an increase of booster voltage. There are several alternative ways in which boosters may be used for particular applications

Transformers

One of the great advantages in the use of alternating currents is the ease with which the voltage may be changed by means of a relatively simple device known as a transformer. Although there are many different types of transformers, and a great variety of different applications, the principles of action are the same in each case.

The basic arrangement is shown in Fig. 33, and consists of a laminated iron core forming a closed magnetic circuit on which two separate windings are mounted. One winding, called the primary, is connected to the A.C. supply, and the other winding, the secondary, produces a voltage which can have any desired value if the respective windings are suitably designed.

The transformer relies for its action upon the fact that when a magnetic field passing through a coil is changed or varied a voltage is produced in the coil. The amount of this voltage is proportional to the number of turns in the coil and to the rate at which the magnetic field varies. With a normal A.C. supply connected to the primary, the field changes at a uniform rate throughout each cycle and a voltage, showing similar variations with respect to time, accordingly appears in the secondary. This induced voltage is virtually a replica of the primary voltage with respect to shape, but its magnitude depends upon the relation between the number of turns in the primary and secondary windings. If the number of secondary turns is greater than the primary, the secondary

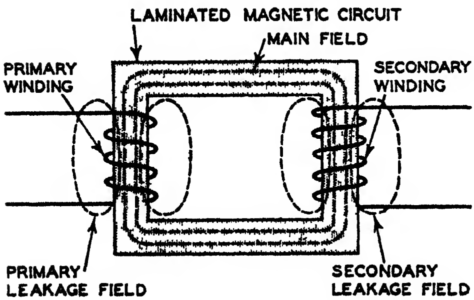


Fig. 33.—Arrangement of Single-phase Transformer.

output voltage will be correspondingly greater than the primary voltage, but if the secondary has fewer turns than the primary it will produce a correspondingly lower voltage than that applied to the primary.

In general, it is approximately true that the ratio of the primary to the secondary voltage is equal to the ratio of the number of primary turns to the number of secondary turns. This ratio is not exact because of leakage effects in the magnetic circuit. Referring to Fig. 33, there is always a certain amount of primary and secondary leakage field, the effect of which is to reduce the secondary voltage below the figure corresponding to the turns ratio.

A further section dealing with transformers as applied to radio will be found on page 199.

Auto-transformers

The transformer effect can also be obtained with a single tapped winding instead of separate primary and secondary windings. The arrangement is called an auto-transformer, and is shown in Fig. 34. If the primary winding represents the whole coil as shown, the secondary voltage will be substantially the same proportion of the applied voltage as the proportion between the turns up to the secondary tapping and the total number of turns. By interchanging the voltages in Fig. 34, so that the supply is connected to the smaller number of turns, a voltage larger than the supply voltage appears across the whole coil. The auto-transformer can thus be used to obtain a higher or lower voltage than the supply, as in the case of the conventional transformer with two separate windings.

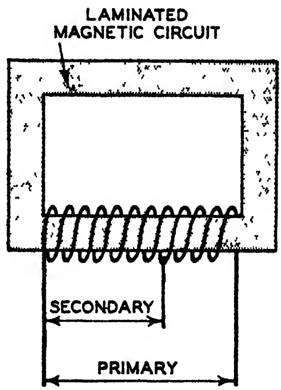


FIG. 34.—ARRANGEMENT OF AUTO-TRANSFORMER.

In practice, the use of auto-transformers is limited to fairly small voltage ratios, one reason being that if a break occurs anywhere in the secondary section of the winding, the primary voltage is applied to the apparatus connected to the secondary (see Fig. 34). With a high primary voltage this would give dangerous conditions. The chief uses of auto-transformers are in A.C. voltage

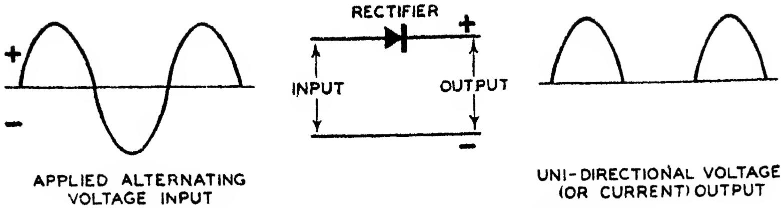


FIG. 35.—ACTION OF SIMPLr FORM OF RECTIFIER.

regulation and for infrequent service such as the low-voltage starting of induction motors.

Rectifiers

There are many applications of electricity where, for technical reasons, D.C. is preferable to A.C. These applications include various forms of traction, and other classes of drive where the smoother speed control obtainable with D C. motors represents an important advantage. For battery charging purposes, a D.C. supply is, of course, essential. In radio apparatus, D.C. supplies are often needed for parts of apparatus which otherwise operate from A.C. mains. In all such cases, it is necessary to have some means of obtaining D.C. from an A.C. source, and this requirement is met by one or other of the numerous forms of rectifiers. This device has the property of passing current in only one direction, so that when an alternating voltage is applied to it, only the half-cycles of voltage corresponding to the direction of conduction through the rectifier are effective in producing current in the circuit.

The principle of rectification is shown in Fig. 35, where the rectifier unit is indicated by an arrow representing the direction in which current may flow through the unit. With an alternating voltage applied as shown, current is passed by the rectifier only during the half-cycles corresponding to the conducting direction. The intermediate half-cycles, which are in the opposite direction, are ineffective, and no current flows through the rectifier during these half-cycles. The output, therefore, takes the form of single pulses of current in one direction with half-cycle rest periods. This is the simplest form of half-wave rectification, but is inefficient because the effect of every alternate half-cycle of input voltage is lost.

With the circuit shown in Fig. 36, use is made of both halves

of each voltage input cycle, thus obtaining what is called full-wave rectification. There are four rectifier units, connected so that whichever way the input voltage is applied, current is able to flow through the rectifier circuit to the output always in the same direction. During the half-cycles of input voltage when point *a* is positive with respect to *c* the current flow is from *a* to *b*, through the output or load circuit and thence from *d* to *c*, this path corresponding to the conducting direction through the two rectifier units in question. With an input voltage in the opposite direction, so that *c* is positive with respect to *a*, the current flow is from *c* to *b*, through the load circuit and thence from *d* to *a*, using the second pair of rectifier units. This means that both halves of each cycle of input voltage are utilized in producing a uni-directional output current. There are alternative circuit arrangements for giving full-wave rectification, according to the type of rectifiers used. In the majority of circuits, a transformer is introduced between the input and the rectifier so as to obtain a particular value of output voltage.

Metal Rectifiers

A widely used form of rectifier is the metallic type, consisting essentially of a number of units formed by depositing a layer of semi-conducting material, such as copper-oxide or selenium, on a metal conducting base. These units, generally in the form of washers, are assembled on rods under pressure, the number of units employed being determined by the voltage. Each unit has the peculiar property of passing current freely when the semi-conducting layer is positive and allowing practically no current to flow in the opposite direction. This form of rectifier has the great advantage of robustness, absence of moving parts and relative simplicity.

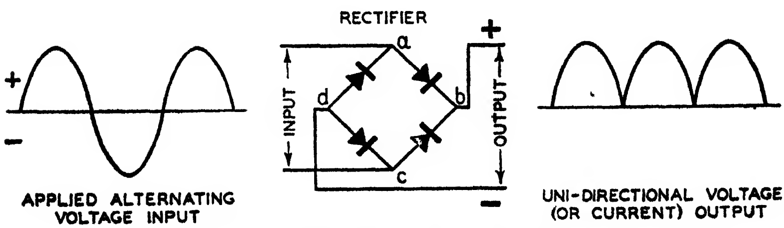


Fig. 36.—Action of Bridge-Connected Full-Wave Rectifier.

Valve Rectifiers

Another type of rectifier is represented by the various kinds of two-electrode valves, or diodes. These consist of a glass tube or bulb containing an electron-emitting member (the cathode) and an electrode (called the anode) which collects the emitted electrons and causes a flow of current so long as it is positive with respect to the cathode. The arrangement of the bulb and its use in a simple circuit are shown in Fig. 37. In this case, the cathode heater is supplied with a suitable voltage from the transformer secondary to provide the heating necessary for the emission of electrons. The action of the tube differs somewhat according to whether it is of the high vacuum or gas-filled type. In a vacuum, only electrons constitute the current

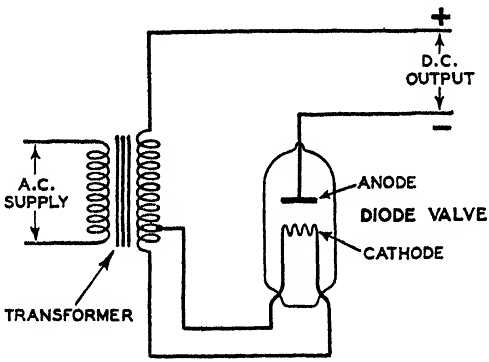


FIG. 37. HALF-WAVE RECTIFIER CIRCUIT USING DIODE VALVE.

The cathode heater is supplied from the transformer secondary to provide the necessary heating for the emission of electrons.

flow, whereas when gas is present it becomes ionized by the electron flow, as a result of which the gas atoms become broken up into their constituent parts, i.e. electrons and ions. The electrons released in this way augment the current flow, which is, consequently, greater than would be produced in a vacuum tube under the same conditions. The rectifying property of the diode valve arises from the fact that electrons can flow from cathode to anode only when the latter is positive with respect to the cathode. The electrons, having a negative charge, are attracted by the positive anode and flow to it all the time it remains positive, thus causing a flow of current through the tube and the external circuit. It is important to note that the flow of electrons in any circuit is always in the opposite direction to which the current is assumed by convention to flow,

i.e. from positive to negative. It is only during the half-cycles when the upper terminal of the transformer secondary is positive in Fig. 37 that current can flow through the rectifier; the anode then being positive with respect to the cathode.

The principles of rectification through gas-filled tubes have been extended during recent years to very large types of rectifier designed for high voltages and currents. These rectifiers are of ironclad construction with water cooling and employ a cathode consisting of a pool of mercury. The A.C. input has three, six or twelve phases, and there is a corresponding number of anodes, from which the discharge, in the form of a powerful arc, passes to the cathode.

ELECTROCHEMISTRY

Some important effects occur when a current is passed through certain liquids and chemical solutions. In the case of water, oxygen is given off at the positive electrode, while hydrogen is liberated at twice the rate at the negative electrode. This action, known as electrolysis, represents the decomposition of water into its constituents, i.e. two parts of hydrogen to one part of oxygen (H_2O). The effect is used on a large scale in practice to produce the respective gases for the numerous industrial applications in which they are used. Commercial forms of electrolytic cells for this purpose are supplied continuously with water and current, the gases being drawn off into separate mains. Large cells are capable of producing as much as 18,000 cubic feet of hydrogen per hour.

When current is passed through chemical solutions, the constituent parts of the materials in solution take part in the conduction. Positive ions, representing molecules with one or more electrons missing from the normal atomic structure, flow towards the negative pole, while negative ions, which have more than their normal complement of electrons, flow towards the positive pole. As a result of this movement, there is a transference of material to the respective poles. For example, in a solution of common salt and water, the salt (sodium chloride) breaks up into ions of sodium and chlorine. The sodium ions are positive, having one electron less than normal, and the chlorine atoms negative, having one more electron than normal. When voltage is applied to the electrodes, the sodium (+) and

chlorine (−) ions move in opposite directions, resulting in the deposition of sodium at the negative electrode and chlorine at the positive. These movements are in accordance with the principle that unlike charges attract each other and similar charges repel.

The transference of materials in this way is utilized in practice for various purposes, notably electro-plating and electro-refining. In electro-plating a pure metal is used for the anode, the articles to be plated forming the cathode. The amount of material deposited is proportional to the current flowing and the time, but is not the same for all materials. In the case of electro-refining, the impure metal forms the anode and is gradually transferred by the electrolytic action to the cathode, where it appears in a pure form, any impurities being left behind as a sediment in the bottom of the cell.

Another important industrial process is the anodizing of aluminium, representing the formation of a very tough and durable oxide film by electrolytic means. The parts to be treated form the anode of the electrical supply to a bath or vat containing chromic or sulphuric acid which is kept at a temperature of about 104 degrees F. by means of suitable heaters. The film deposited under these conditions imparts to aluminium a remarkable resistance to corrosion which otherwise causes difficulty, especially in parts exposed to the action of sea-water.

CHAPTER IV

HOW ELECTRICAL QUANTITIES ARE MEASURED

THE use of correct quantities has always been acknowledged as one of the essentials of successful achievement in the production of any commodity. Radio and the application of electricity generally are no exceptions to this rule. Just as it is necessary, even when making a cake, to measure or weigh out the various ingredients to ensure a product to suit the taste and digestion, so with a wireless set it is imperative to make sure that the right current at the correct voltage is being supplied to the various components so that the resultant sound emission is a faithful reproduction of the original. For instance, given a good circuit, an output of the best quality can only be obtained by treating the valves in the right way.

This means having the correct voltages all round, as recommended by the valve manufacturer. These voltages can be measured by means of a voltmeter, and the accuracy of the readings obtained depend upon the particular type of instrument employed. Some knowledge of the various measuring instruments available and their characteristics and applications is therefore desirable, especially in radio work as many improvements in performance can be made and faults rapidly diagnosed by checking up voltage and current values with the correct type of meter.

Fundamental Discoveries

As soon as electrical research became an established branch of science, it was apparent that some means of measuring this new form of energy was needed, and the early work of Oersted, Biot and Savart, contributed largely to the successful evolution of the measuring instruments now in every day use.

Professor Oersted found that when a freely suspended magnet was placed near a current carrying conductor, the magnet was

deflected to one side. This discovery formed the basic principle of the galvanometer, an instrument which can be specially calibrated for measuring very small currents and voltages, or used as an indicator for detecting the presence of current flow in a conductor.

Biot and Savart were engaged in electromagnetic research and determined the laws of force between a magnet and a current carrying conductor. These observations were developed further by Ampere who discovered similar relations existing between two conductors carrying a steady current.

The design of electromagnetic measuring instruments is based on the principles evolving from this research and their subsequent commercial development has provided us with accurate and reliable equipment which is now almost universally employed for measuring current and voltage.

Several other varieties, such as the hot-wire and electrostatic types have been developed for the same purpose but they have certain disadvantages, and their application is limited.

In addition, there are many kinds of meters for measuring energy and power, such as the electrodynamic, or dynamometer type, the construction of which, is based upon the mutual forces existing between movable and fixed sections of a circuit carrying current.

The type of meter normally used for radio purposes gives a direct indication of the quantity to be. measured, by means of a pointer moving over a graduated scale, and is known as an *indicating* instrument. Recording instruments which reproduce their readings graphically on a chart and supply meters, which register the total energy consumed over a period by means of a series of dials, are used extensively commercially.

As this book is primarily concerned with radio, most attention is given to the various forms of instruments normally encountered in this field and only a brief reference is made to typical examples of other meters.

Classification

The conventional method of classification for electrical measuring instruments is primarily in accordance with their mode of operation and, therefore, the types used for measuring current, voltage and power may be grouped as follows ;—

1. *Electromagnetic*
   (*a*) Polarised moving iron.
   (*b*) Moving iron.
   (*c*) Moving coil.
   (*d*) Electrodynamic.
   (*e*) Induction.
2. *Electrostatic*
   (*a*) Electrostatic voltmeters.
3. *Electrothermal.*
   (*a*) Hot wire.
   (*b*) Thermo-couple.

Principle of Operation

The operation of these meters is dependent upon a moving unit incorporating an indicator, or pointer which is arranged to move over a graduated scale. The unit is actuated by the current to be measured and takes up a position of equilibrium proportional to the current so that the pointer comes to rest somewhere between the zero and maximum scale divisions. Some form of controlling agent such as a spring, or gravity arrangement, is employed to ensure that the deflection is proportional to the deflecting force and also to return the moving unit to the zero position when the deflecting force is removed.

Damping

Most forms of indicating instruments in use to-day are what is known as *dead-beat* types. This means that when current is passed through the meter coil, the pointer moves up to the correct reading without vibrating about the mean position, thus enabling accurate and quick readings to be taken. This effect is achieved by the use of a *damping* arrangement. The methods of damping usually employed depend on air friction (pneumatic), liquid viscosity (oil), or the generation of electrical eddy currents (electromagnetic).

Air friction is the most popular method used for the less expensive forms of ammeters and voltmeters. The system comprises a light piston attached to the moving unit by a crank, and located in a cylinder which is closed at one end, as shown in Fig. 1. The piston is a loose fit in the cylinder so that air

can escape round it slowly when compressed and yet sufficient compression is retained to impart a cushioning action to the piston and thus damp out any tendency to oscillate.

A similar principle is applied for liquid damping but, in this instance, a disc immersed in oil is attached to the crank in place of the piston, and the oil, because of its high viscosity or internal friction, offers a resistance to the movement of the disc.

The eddy current method of damping is illustrated in Fig. 2 and, in its simplest form, consists of a disc of conducting material attached to the moving unit which is allowed to rotate or oscillate in the air gap of a permanent magnet. The movement of the disc is restrained by the presence of eddy currents in it which are generated when the disc cuts the magnetic flux of the permanent magnet. These eddy currents tend to oppose the forces producing them and thus slow down the movement of the disc.

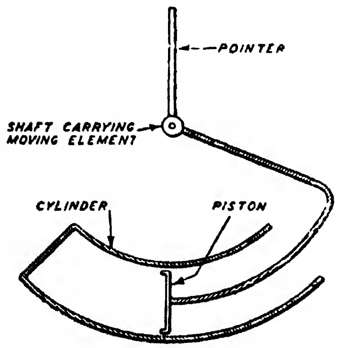


FIG. 1.—PNEUMATIC DAMPING.

Meter Scales

The scale of indicating instruments are classed generally as *linear* or *non-linear*. Linear scales are not necessarily straight as the name implies, but are usually in the form of an arc. They are called linear to denote that they are evenly graduated over the whole length of the arc, with equal sub-divisions. Moving coil instruments are fitted with this type of scale as they incorporate a permanent magnet having a constant field which reacts with the current passing through the moving coil and, therefore, the torque or motive power required to rotate the coil varies directly with the value of this current.

All other types of meter have non-linear or unevenly divided scales, apart from the wattmeter which is only an apparent exception as the force required to rotate the coil and pointer is obtained by the reaction between the voltage and current coils, and therefore its energy comprises two elements, volts and amperes, either one alone resulting in a non-linear scale.

The reason for uneven scales is that these particular meters have no constant auxiliary source of energy, such as the permanent

magnet of the moving coil meter and, therefore, the torque at any instant is proportional to the energy in the coil at that instant, i.e., it is proportional to the square of the current and is said to follow a *square law*. Thus the torque is equivalent to I^2R, where I is the instantaneous current value and R is the resistance of the coil, which is assumed to be constant. This is illustrated in the following table and it will be noted that although the current through the meter coil increases only by 1·0 ampere stages, the increase in torque is much more rapid as the current values rise.

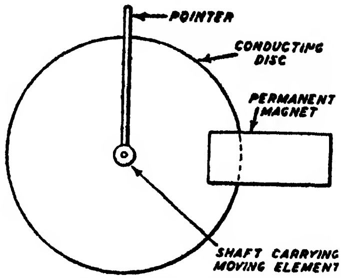


FIG. 2.—ELECTROMAGNETIC DAMPING.

The movement of the meter coil and the pointer is dependent upon this torque and increases in the same proportion, resulting in a scale which tends to be cramped at the zero end and open at the maximum readings.

Current (Amps) Coil.	*Torque. (I^2R.)*	*Torque increase per amp. increase.*
1·0	1·0×R	
		3·0×R
2·0	4·0×R	
		5·0×R
3·0	9·0×R	
		7·0×R
4·0	16·0×R	
		9·0×R
5·0	25·0×R	
		11·0×R
6·0	36·0×R	
		13·0×R
7·0	49·0×R	
		15·0×R
8·0	64·0×R	
		17·0×R
9·0	81·0×R	
		19·0×R
10·0	100·0×R	

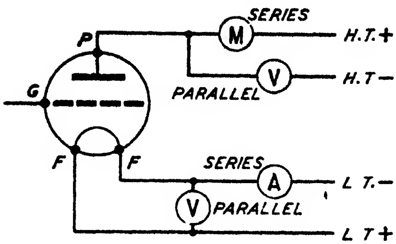


FIG. 3.—METHOD OF CONNECTING VOLTMETERS, AMMETERS AND MILLIAMMETERS IN A CIRCUIT

Ammeters and Voltmeters

Ammeters measure the current flowing in a circuit and normally have scales which are graduated or calibrated in amperes, milliamperes or microamperes. Voltmeters are used to measure the potential difference between two points in a circuit. The calibration of voltmeters is usually in volts, millivolts or microvolts.

The main difference between the two instruments of the same type or design is in the resistance of the operating coil, identical moving units may be used for either meter. An ammeter is connected in the positive or negative lead in series with a circuit, as shown in Fig. 3 and, therefore, must have a low resistance coil, otherwise the readings would be incorrect as the coil would absorb an appreciable amount of power.

The range of an ammeter can be varied by connecting shunt resistances in parallel with the coil, as illustrated in Fig 4. A shunt resistance consists of a slab or strip of low resistance metal, designed so that, with maximum current flowing, the voltage drop across it is sufficient to give a full scale deflection of the ammeter. In other words, the current is divided between the instrument coil and the shunt and only a fraction of the current flows through the coil, the pointer reading, therefore, indicates the potential difference across the shunt.

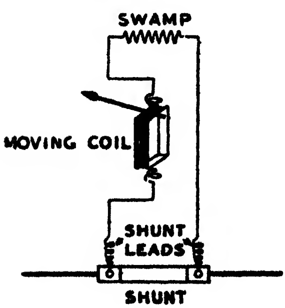


FIG. 4.—CONNECTION DIAGRAM OF MOVING COIL SHUNTED AMMETER.

If the resistances of the shunt and ammeter coil are known, the current flow in each component can be calculated for a number of current values. Therefore, the relation between the pointer deflection and the value of the current through the coil and hence the total current can be deduced and the ammeter calibrated accordingly.

For currents exceeding thirty amperes, or thereabouts, such shunts are normally placed externally to the instrument and great care must then be taken

either to use the shunt leads provided by the makers or leads of approximately the same resistance, otherwise the correct proportion of the total current will not be shunted and the readings will be unreliable.

A voltmeter is connected in parallel across the points of a circuit where the difference of potential is to be measured. The resistance of the operating coil must, in this instance, be as high as possible, to limit the amount of current consumed by it, or else a drop in potential due to the meter would occur and the pointer indication would not represent the true potential difference across the circuit. Voltmeter ranges can be modified by connecting resistances, usually called "resistors" in series with the coil. To ensure accurate readings, these resistors are normally made of manganin, or some similar material having a negligible temperature coefficient, i.e., its resistance is unaffected by changing temperatures.

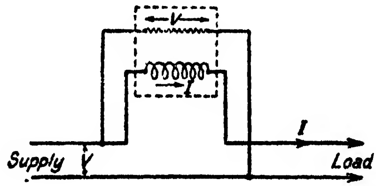


Fig. 5.—How a Wattmeter is Connected in a Circuit.

Showing the two separate connections, one across the potential and the other in series with the load.

Wattmeters

The measurement of the power of a D.C. circuit at any instant can be achieved by means of an ammeter and voltmeter as the power in watts is the product of the current and the voltage. With A.C. circuits, however, the instantaneous values are always changing and as these circuits are often inductive or capacitive, the current and voltage waves may be out of phase as we have already shown in Chapter III.

To measure A.C. power correctly, therefore, employing an ammeter and a voltmeter, would necessitate the use of a third instrument to measure the phase difference. The normal practice, however, is to combine these three instruments in one which will give a direct reading of power in watts.

A wattmeter has two separate coils comprising a potential winding of comparatively high resistance, equivalent to a voltmeter coil, which is connected across the circuit and a fairly low resistance current coil which is connected in series with the load. The method of connecting a wattmeter in a circuit is illustrated

in Fig. 5. The two most popular forms of wattmeter namely, the dynamometer and induction types are referred to later under their respective headings.

Supply Meters

These meters, as we have already mentioned, record on a system of dials, the energy supplied over a period, i.e., all instantaneous readings are summed up or *integrated* over a definite period of time and the dial readings obtained are in either ampere-hours or watt-hours.

There are many varieties of commercial integrating meters, including electrolytic, clock type and motor meters. The latter type is normally employed for A.C. work although the D.C. meters can be used in A.C. circuits if suitable rectifiers are incorporated. As the induction watt-hour meter is almost universally employed in A.C. circuits, a brief description of a typical meter is given later, in the paragraphs dealing with induction meters.

ELECTROMAGNETIC INSTRUMENTS.

Moving Iron Meters

This type of meter is used quite a lot for radio work, but where very great accuracy is not required. They can be obtained in the form of ammeters, milliammeters, or voltmeters and their ranges may be from a few milliamperes or volts upwards. Shunts are not normally used with these instruments, the higher ranges being obtained by using appropriate windings. Resistors, however, can be employed with the voltmeters. There are two distinct varieties of moving iron meter known as the polarised and standard types, the latter being the most popular commercially as they are suitable for either A.C. or D.C. measurements.

Polarised Type—This type consists of a pointer movement with a small, specially shaped vane made from iron sheet, which is fixed to the pointer spindle forming the moving system ; the spindle which carries the pointer, balancing weight and iron vane is then mounted between two pivot screws or bearings, being free to rotate. The movement is usually mounted in a brass frame, which also has a coil of insulated copper wire wound on a small laminated iron core and fixed close to the moving-iron vane.

As there are no control springs, a permanent magnet is fitted in such a position that it acts on the movement and keeps the pointer on the zero mark. When current is passed through the coil winding the core becomes magnetised, thereby producing a strong magnetic field, repelling or attracting the iron vane on the spindle and so deflecting the pointer.

The calibration is made by checking against a standard meter and adjusting the coil and magnet to conform with the required reading on the dial.

The polarised moving iron meter is only suitable for measuring direct current, and can also be used as a polarity indicator. The chief advantage of this type of meter is ease of manufacture, the absence of springs, good damping and low cost. Its uses are limited to measurements which do not require great accuracy, usually within 5 per cent.

Standard Moving Iron Type—This is the most popular type of meter for use on A.C. but is quite suitable for D.C. application. The movement is very similar to the polarised pattern, but has a spiral spring fitted to the pointer to keep it on the zero mark. The meter comprises a solenoid having inside it either a single pivoted vane, or two irons, one fixed and the other pivoted. When a direct or alternating current is flowing, the pivoted vane is attracted into the coil or, when two irons are used, the irons are of similar polarity and therefore repel each other. This latter design is in more common use and is known as the repulsion type of moving iron meters (see Fig. 6.).

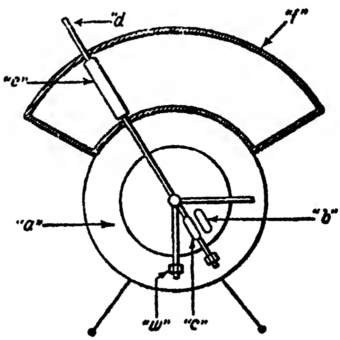


FIG. 6.—ESSENTIAL DETAILS OF THE MOVING IRON AMMETER OR VOLTMETER.

(*a*) Coil; (*b*) fixed iron; (*c*) moving iron; (*d*) pointer; (*e*) pneumatic damping vane; (*f*) cylinder; (*w*) weight.

Characteristics of the Moving Iron Meter

The main advantages of the moving iron meters are in the low initial cost and general robustness of the design. The disadvantages are that they have non-linear scales and are subject to errors due to wave form, frequency variation and hysteresis. Their accuracy is also affected by strong magnetic fields and temperature changes which

may alter the resistance of the operating coils. All these errors, however, can be reduced to small limits by careful design and the non-linearity of the scale can be corrected to some extent by the accurate shaping and positioning of the irons with relation to the operating coil.

Moving Coil Meters

Moving coil meters are acknowledged to be the best type for all direct current measurements. They are more economical in current consumption, very sensitive to voltage or current fluctuations, and maintain a high degree of accuracy over long periods. Although they are more expensive than the moving iron type, they are essential for serious radio work and especially where accurate readings are required, the accuracy being about 2 per cent.

The principle and construction are more complicated than in the cheaper moving iron models and call for greater accuracy in the machining and assembly of the numerous small parts. The two main features of the design of moving coil meters are the permanent magnet and the complete moving coil system, as shown in Fig. 7.

A well-aged tungsten steel magnet is usually employed with fitted soft-iron pole pieces. A cylindrical soft iron core is located centrally between the poles to give a high flux density across the air gap between the pole pieces and the core.

The pointer is fixed to a small coil of wire wound on a light metal former of rectangular shape. The electrical connection is made through fine spiral springs mounted on small brass bushes which are fitted with a highly polished hard steel pivot or spindle and fastened to the coil at each end. The movement is then mounted in a frame between two jewelled pivot screws and fixed between the pole pieces in such a way that it can rotate through a considerable arc round the soft-iron core, concentric with the magnetic field, as illustrated in Fig. 8.

When current is flowing in the coil, it tends to set up a magnetic field at an angle to the field of the permanent magnet, and the reaction between the two fields causes a deflection of the coil and the attached pointer, which is in direct proportion to the amount of current passing.

The damping is electromagnetic and is provided by the generation of eddy currents in the metallic former of the moving coil.

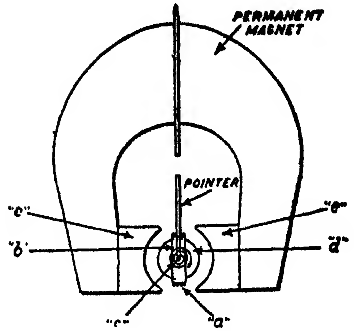


Fig. 7.—Diagram showing Essential Construction of Moving Coil Ammeter or Voltmeter.

(a) Coil of wire, (b) former; (c) jewelled bearings; (d) soft iron core; (e) permanent magnet.

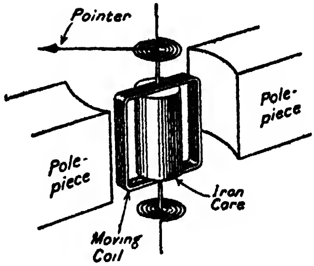


Fig. 8.—Details of Moving Coil Instrument.

Note the two control springs which supply the control torque and the paths for the current into and out of the moving coil.

This method of construction permits a full deflection of the pointer with a very small consumption of current, producing good damping and dead-beat readings.

Characteristics of the Moving Coil Meter

These instruments are only capable of measuring direct current and have linear scales which is a big advantage from the point of view of clarity of reading.

The instrument is essentially a milliammeter and is also quite suitable for voltage measurement. When, however, it is required to measure a current exceeding about ½ ampere, the meter is used in conjunction with a shunt, as shown in Fig. 4. When this type of meter is used to measure voltage, it is usual to insert resistances in series with the moving coil. This resistance is normally mounted inside the instrument casing for voltages up to 600 or used externally for voltages exceeding this value.

Rectifier Type of Moving Coil Meter

The moving coil instrument, although normally limited to D.C. applications, can be adapted for A.C. use by the incorporation of suitable metal rectifiers or small thermo-couples. The bridge method of connecting the rectifiers to give full-wave rectification is illustrated in Fig. 9. In effect, it simply employs a moving coil instrument with the addition of a rectifier to rectify

the alternating current. A form of direct current which can be measured by the moving coil instrument is thus produced.

Apart from the linear scale possessed by this instrument, another advantage is the fact that it provides an easy means of obtaining an A.C. milliammeter with a low impedance. Prior to its introduction, the only low impedance A.C. milliammeter available was the thermo-couple type with its consequent troubles due to overloads.

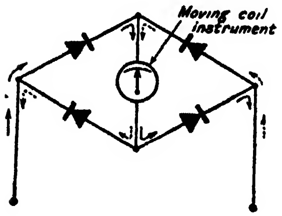


FIG. 9.—RECTIFIER TYPE OF INSTRUMENT.

A diagram of connections showing how the rectifiers are connected to a moving coil instrument to enable it to read on an A.C. circuit.

The chief disadvantage of rectifier meters is the error introduced by variations in wave form since the instrument measures the mean value of current although it is scaled to read R.M.S. values.

Multi-Range Moving Coil Meters

From the radio service engineer's angle, the multi-range testing set is an excellent investment as it comprises ammeter, voltmeter and often ohmmeter in one unit. The more expensive varieties include metal rectifiers and can be used on both A.C. and D.C. circuits. A wide range of readings, from milliamps and millivolts upwards, is obtainable with a single instrument. Voltage or current selection is made by a change-over switch on the body of the meter and the scale ranges for voltage and current can be varied by means of internally fitted resistances and shunts, controlled by rotary switches which are marked to show the particular factor to be applied to the indicated reading.

The most simple form of multi-range testmeter circuit is that of the D.C. Avo Minor illustrated in Fig. 10. With the universal type of meter, the rectifiers for measuring alternating circuit voltages are normally connected in the form of a four-unit bridge as illustrated in Fig. 9 in conjunction with a suitable switching circuit.

The larger instruments are developments of these fundamentals and incorporate a small transformer which will enable alternating currents to be measured, some form of automatic overload protection, more complicated interlocking switching circuits, and movements of differing degrees of sensitivity.

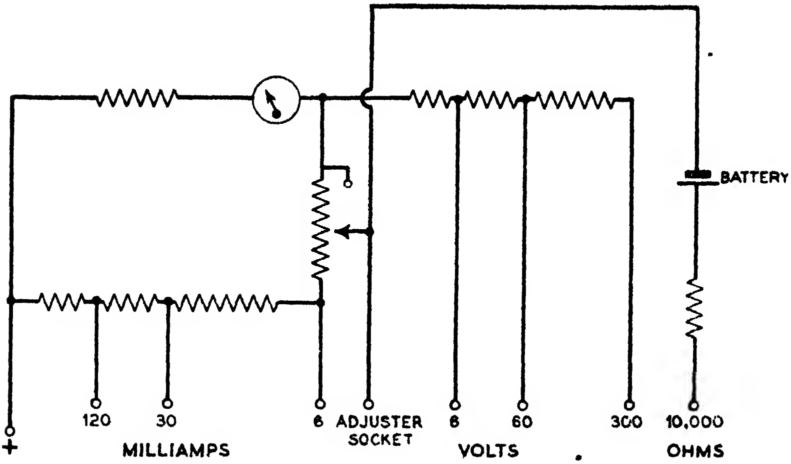


FIG. 10.—CIRCUIT DIAGRAM OF THE D.C. AVO MINOR.
(Automatic Coil Winder & Electrical Equipment Co., Ltd.)

Some models incorporate small cells for resistance measurements and have scales calibrated directly in ohms. Others, while embodying the features already mentioned, can be used for the measurement of power, capacity and decibels. In addition, various accessories are available, usually in the form of external shunts and resistances, for increasing the ranges beyond the normal scope of the instrument.

Electrodynamic or Dynamometer Instruments

This type of instrument is available in the form of ammeters, voltmeters or wattmeters which depend for their operation upon the mutual forces between movable and fixed coils in a circuit carrying current. The meters are suitable for either direct or alternating current application and the particular form i.e., ammeter, voltmeter, or wattmeter, is dependent upon the design and connections of the two coils. With wattmeters, the scales are linear but for ammeters and voltmeters, square law scales are employed.

Ammeters and Voltmeters—These meters are capable of great accuracy and are largely favoured, on this account, for laboratory use. The instrument consists, fundamentally, of a set of fixed coils which surrounds a set of moving coils, as shown in Fig. 11. The moving coils are coupled to the pointer and the damping

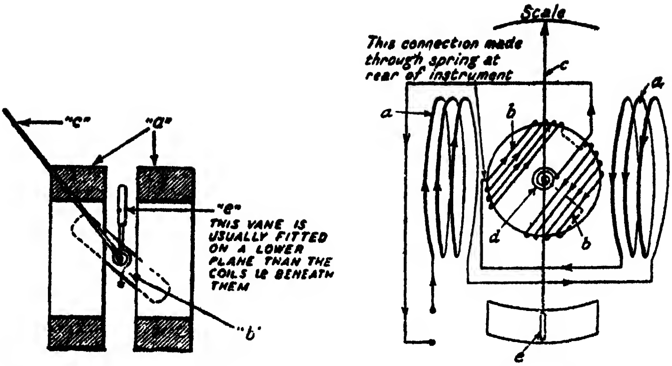


FIG. 11.—THE ESSENTIALS OF THE DYNAMOMFTER INSTRUMENT.

The operation depends on the attraction between two sets of coils carrying current: (*a*) set of fixed coils; (*b*) moving coils; (*c*) pointer; (*d*) two control springs; (*e*) pneumatic damping arrangement.

vane, the whole of the moving unit being suspended in jewelled bearings.

The instrument is shielded from external fields by enclosing the complete movement in a soft iron case, which is sometimes laminated.

The driving torque depends upon the interaction of the fluxes caused by the current flowing in the two sets of coils. Control torque is generally provided by spiral springs which also serve to lead the current into and out of the moving coil.

The damping is usually of the pneumatic form similar to that used in the moving iron type of meter.

With ammeters, the fixed coil carries the main current and the moving coil is normally connected across a suitable shunt which is in series with the fixed coil. Voltmeters have both coils arranged in series, together with a suitable resistance having a negligible temperature coefficient.

Wattmeters—A similar construction is employed for wattmeters, but in this instance the main current taken by the circuit, whose power is to be measured, is passed through the fixed coil, and the moving coil carries the potential current. The windings of the fixed coil are, therefore, of a comparatively few turns of heavy section copper wire and those of the movable coil of a fairly large number of turns of fine wire having a high resistance similar to a voltmeter.

These wattmeters are mainly employed in the laboratory and

test room, where they are used as standards both for the measurement of A.C. and D.C. power, and also as transfer standards from one source of energy to the other.

Induction Meters

This class of meter is only suitable for use with A.C. The operation depends on the passage of alternating current through suitably located coils, producing a rotating magnetic field which will interact with a metallic disc suspended near to the coils and cause the disc to rotate. As with the electrodynamic types, ammeters, voltmeters and wattmeters operating on this principle are available.

Ammeters and Voltmeters—The instrument illustrated in Fig. 12 comprises a specially shaped metallic disc (generally made of aluminium or suitable alloy) coupled to a pointer and suspended in jewelled bearings. The disc passes through two air-gaps, the first located in an electromagnet and the second in a permanent magnet. The laminations of the electromagnet are partially embraced by a thick copper loop known as a shading coil.

The effect of an alternating current in the coil is to produce eddy currents in that portion of the disc under the poles and not screened by the shading coils. In addition, similar currents will be produced in the shading coil and the attraction set up between the two sets of currents will cause the disc to rotate. The control torque is obtained from a spiral spring attached to the moving unit. Electromagnetic damping is provided by inter-action between eddy currents in the disc and the flux of the permanent magnet.

These instruments are simple, robust and not permanently affected by overloads. They have non-linear scales and read R.M.S. values. The fairly large errors due to temperature frequency and wave form variations are the main disadvantage, but these errors have been considerably reduced in modern designs by the use of special alloys and a particular design of shunt circuit. Also the cramped scale characteristics have been improved by modifications to the shape of the moving element.

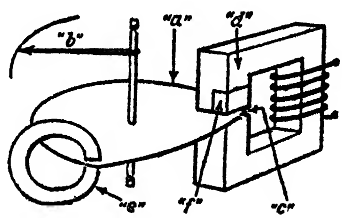


FIG. 12.—DETAILS OF AN INDUCTION INSTRUMENT.
(*a*) Metallic disc; (*b*) pointer; (*c*) air-gap of electromagnet; (*d*) electromagnet; (*e*) permanent magnet; (*f*) shading coil.

Wattmeters—This form of induction meter differs from the ammeter or voltmeter in so far that two coils are used to produce the rotating magnetic field, in place of the one coil with a shading loop. One coil is energised by a current which is proportional to the voltage across the circuit or its equivalent. This coil is made highly inductive so that the current, and hence the flux, lags 90 degrees behind the voltage.

The second coil is energised by the load current or its equivalent and is made non-inductive so that the current and the voltage are in phase. Thus, the two fluxes displaced one from the other by 90 degrees, interact upon a metallic drum or disc suspended near them and cause it to rotate. The drum or disc is coupled to a pointer and a suitable control spring. Damping is usually electromagnetic and is provided by a metallic disc mounted on the rotor shaft and arranged to move in the air gap of a permanent magnet.

The characteristics of these wattmeters are similar to those of the induction ammeters and voltmeters, and they have a large field of application as switchboard instruments. When measurements are required on polyphase circuits, it is usual to couple a number of single wattmeter elements to a common rotor system.

Induction Watt-Hour Meters

The basic form of the single-phase induction watt-hour meter is illustrated diagrammatically in Fig. 13. It consists of a light aluminium disc mounted on a vertical spindle which is supported by a cup-shaped jewelled bearing at the bottom end and has a spring journal bearing at the top end. The disc, which is gear coupled to a revolution counter registering kilowatt-hours, rotates in two air-gaps, one belonging to a braking permanent magnet and the other to a combined electromagnetic system energised by the voltage and current windings.

The voltage winding, consisting of a single coil, is located on the centre arm of the upper section of the electromagnetic system and is made highly inductive so that the current, and therefore the magnetic flux from the voltage pole, lags approximately 90 degrees behind the voltage. Two current coils are situated on the two poles in the underside of the disc and the magnetic fields produced in these poles are very nearly in phase with the main current but are of opposite polarity. The current coil fields produce eddy currents in the disc which react with the

field from the voltage pole and thus create a driving force proportional to the power in kilowatts in the main circuit, causing the disc to rotate.

The speed at which the disc rotates is controlled by the permanent magnet and a magnetic shunt is fitted to this braking magnet system so that the damping effect can be adjusted as required, alternatively, the position of the magnet in relation to the disc can be varied.

Power Factor Compensator

A power factor compensator is necessary so that the meter will register accurately on inductive circuits and this is normally fitted in the form of a short-circuited loop of copper or other conducting material round the centre pole of the voltage magnet. A current is induced in this loop by the voltage flux and causes a further displacement of the flux. By altering the position of the loop or varying its resistance, this displacement can be adjusted to suit the particular circuit involved.

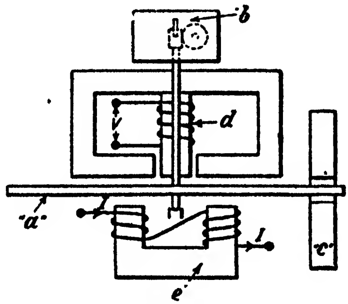


FIG. 13.—DIAGRAM SHOWING ESSENTIAL PARTS OF AN INDUCTION WATT-HOUR METER.

(*a*) Metallic disc; (*b*) counter; (*c*) braking magnet; (*d*) voltage winding; (*e*) electromagnet with current windings.

Light Load Adjustment

A further compensating device, known as the light load adjustment, is essential as the accuracy of the meter is affected on light loads by friction in the bearings. Several methods are used, one of the most popular being by means of two adjustable short-circuited loops placed in the leakage gaps of the voltage electromagnetic system. These loops have the effect of upsetting the symmetry of the leakage flux, which results in a slight torque tending to drive the disc in one direction or the other.

The loops are adjusted so that when no current is passing through the current coil, the torque produced is just sufficient to overcome the friction in the bearings, without actually rotating the disc.

THERMAL TYPE METERS.

Hot Wire Meters

The operation of this type of instrument depends upon the expansion of a wire, usually made of platinum iridium alloy, which is heated due to the passage of current. The sag in the wire is taken up by a spring, the movement being magnified by a system of levers and transmitted to the pointer by a fibre or silk strand which is passed round a pulley coupled to the pointer and fastened to the spring. The moving system is completed by a metallic damping disc, which is used in conjunction with a permanent magnet. The movement is suspended in jewelled bearings, and the complete unit is usually mounted on a special alloy compensating plate.

Thermo-couple Meters

The original hot wire instrument has now been superseded by the modern version comprising a sensitive moving coil meter used in conjunction with a thermo-couple which is attached to a heater wire, as already described on page 50.

Characteristics of the Thermal Type Meter

Although the instrument is relatively simple and cheap to produce, it is not used commercially for the following reasons :—

1. The driving torque being dependent on the heat produced in the wire is proportional to the square of the current and therefore the scale is non-linear.
2. Inaccuracies are introduced by changes in the ambient air temperature.
3. The instrument has a very sluggish action since the wire takes a short time to reach its final temperature.
4. The wire, particularly in ammeters, is liable to fuse due to overload.
5. The amount of power consumed by the instrument is usually heavier than in other types.

The most useful application is in high-frequency circuits such as those used in radio work, because the forces operating the pointer are practically independent of frequency. The thermo-couple type of meter is normally employed for accurate measurements of radio-frequency aerial and feeder currents.

ELECTROSTATIC VOLTMETERS

These instruments are now generally limited to the laboratory or to some special form of fault indicator and are normally only suitable for the measurement of high voltages, although low reading meters have been developed for special applications. The operation depends upon the electrostatic attraction existing between two plates charged at different potentials; one plate is fixed, while the other, which is coupled to the pointer, is free to rotate on jewelled bearings. The instrument is, in effect, an air condenser, in which the moving plate increases or decreases the capacity.

The driving torque is due to the electrostatic force existing between two systems at different potentials and the control torque is generally provided by a spiral spring or gravity. Pneumatic damping is normally employed.

Characteristics of the Electrostatic Voltmeter

The chief advantages of electrostatic instruments are their small power consumption and the fact that they are unaffected by temperature changes and stray magnetic fields.

Apart from the cramped, non-linear scale, the chief disadvantage of these instruments is the comparatively high voltage which must be applied to the vanes with the consequent source of danger due to breakdown of the instrument, although this has been overcome in recent models by the inclusion of a safety resistance which is in series, its function being to limit the current if any sparking-over occurs.

Errors due to friction are difficult to avoid since the operating torque is so small and in addition, leakage currents, intensified by any traces of dampness, may cause inaccuracies.

RADIO APPLICATIONS OF VOLTMETERS AND MILLIAMMETERS.

There are many uses for instruments in wireless work varying from the simplest check on battery voltage to the highly specialised use of frequency measurement equipment. In this section, we only propose to deal briefly with some of the elementary tests which can be safely undertaken without any specialised knowledge and which will illustrate the uses of these particular instruments.

Voltmeters

Voltmeters should have a high resistance, which is usually about 200 ohms per volt for ordinary radio measurements, except in cases where the meter may be used for taking voltage readings from mains-operated sets or mains eliminators, when an extra high resistance voltmeter is essential. The resistance in this case should be at least 400 or 500 ohms per volt of the meter scale.

This is a most important point when measuring the anode voltages with A.C. mains receivers, as it greatly affects the accuracy of the reading. Actually, the higher the total resistance of the meter, the greater will be the accuracy obtained. This will be clearly realised when it is remembered that the capacity or output of the power unit is limited, being from 10 milliamperes upwards, and as the meter consumes, say 2 milliamperes, the error in voltage reading will be at least 2 per cent. for full scale deflection when used with a power unit of 100 milliamperes output ; provided, however, the power unit capacity and current consumption of the voltmeter are known the necessary error can be taken into consideration on all readings.

Moving coil meters of reliable manufacture can be used in any circuit continuously, without fear of causing injury to the meter, but care must be taken to ensure that no overloading occurs or the insulation of the coil winding may become charred and cause erratic or wholly inaccurate readings.

For battery tests, one of the cheap portable moving iron voltmeters is very useful, having two scales, 0–6 volts for low-tension accumulator or grid bias battery tests and 0–120 volts for high-tension battery tests.

Reading of low-tension, high-tension or grid bias battery voltages should always be taken with the receiver in operation. Low-tension accumulators should never be worked below 2 volts per cell, and high-tension batteries should be renewed when the voltage has dropped 25 per cent. Grid bias batteries require renewing when the volts have dropped 20 per cent.

Milliammeters

The milliammeter is the most useful instrument for locating faults and checking the quality of reproduction in radio receivers. Standard models can be obtained with scales from 2 to 1,000 milliamperes (1 ampere). Probably the most useful single-scale

meter for general radio work is a meter scaled 0–35 or 50 milliamperes. Its chief uses are for measuring the individual anode current of any valve, for taking emission tests in conjunction with a voltmeter, for indicating distortion in reproduction and for tracing faults of various kinds in radio circuits.

Emission Tests—While there are universal testing sets available for taking complete emission tests of valves, this can also be done quite quickly and accurately with a suitable milliammeter by breaking the anode lead so that the meter can be connected in series with the plate of the valve and the positive H.T. tapping. To make a complete check, it is necessary to know the characteristics, which are usually supplied by the valve manufacturers on the valve carton and frequently in a separate leaflet.

It will be seen from the characteristic curve that, if a certain voltage is applied to the plate grid and filament, the anode or plate current should be x milliamps. The valve should work on the straight part of the curve, and should give a steady reading. In some critical circuits, the extra resistance of the meter or the presence of the meter leads may cause instability or set up a howl, and to prevent this effect a 2–mfd. condenser should be connected across the meter terminals.

If the milliamp. reading is too low, the valve may have lost its emission, but, before replacing with a new valve, make certain by testing with a good voltmeter that the correct volts are being applied to the filament, and it is important to make this check directly across the valve-holder connections. When the anode current is too high, the grid bias voltage is too low or there is a leaky grid connection or faulty coupling condenser.

No current reading usually indicates a faulty valve or one that has lost emission through age or misuse. Before replacing, carefully check for broken or faulty connections in the valve holder and in the anode circuit back to the H.T. supply, any anode components being short-circuited. Constructional faults are sometimes found in the valves themselves ; a set may function normally for a certain period when switched on and then suddenly cease to operate. One of the valves is usually the source of the trouble, having a bad internal joint which just breaks contact when the valve is thoroughly heated. Leaving a milliammeter in the anode circuit of each valve in turn for some time will locate the fault.

The milliammeter should show a steady current reading when no signals are being received, and if a continual variation is shown, the trouble is usually due to the valve itself, as pointed out in the previous paragraph, or to a faulty connection in the filament, grid or anode circuit. Check the connections to the valve-holder and all wiring joints.

Indicating Distortion—Poor quality reception in a radio receiver usually indicates that distortion is taking place, and a milliammeter connected in the anode circuit of the output valve will give a visual indication. If the set is working correctly, the milliammeter should show an almost steady reading, but if the pointer gives violent kicks up or down, distortion is undoubtedly present, either due to excessive overloading of a valve or to incorrect high-tension or grid bias voltages.

Reference to the valve manufacturers' data will show if the valve is being overloaded. If the milliammeter pointer kicks upwards, the valve or valves are overbiased and should the point kick towards zero, underbiasing is indicated.

CHAPTER V

RADIO WAVES AND BROADCASTING

THE alternating currents used for electric power supplies have frequencies of up to 100 cycles per second, which are known as POWER FREQUENCIES. Wireless signals are also composed of alternating currents and voltages, but in this case the frequency is very much greater than power frequencies. Imagine the sequence of events in a complete cycle being speeded up so that instead of fifty complete cycles occurring in one second as many as 500,000 occur—*i.e.*, 10,000 times as many. Thus one complete cycle occupies not $\frac{1}{50}$th of a second but $\frac{1}{500000}$th of a second, a time so short that it is almost impossible to realize what it means. Suppose that we started to count from 1 up to 500,000 at the rate of one per second without stopping for food or sleep. It would take us nearly six whole days of twenty hours apiece to reach the half-million. Now try to imagine that all this could happen in one second, and we get a vague idea of how quickly the current in a wireless transmitter or receiver can alternate.

Radio Frequencies

The frequencies of wireless signals are called RADIO FREQUENCIES; they vary from about 10,000 cycles per second to well over 1,000,000,000 cycles per second. The mathematician has a shorthand way of writing large numbers like these. He counts the number of noughts in the number and in place of 1,000,000,000 would write 10^9. The small number 9 at the top of the 10 is called an INDEX, and 10^9 means 10 multiplied by itself for 9 times. That is to say, a number 1 followed by 9 noughts. Thus 10^6 means $10 \times 10 \times 10 \times 10 \times 10 \times 10$, the answer being one million (1,000,000). If we want to write a number like 1,500,000—*i.e.*, one and a half million—we write it in this way: $1{\cdot}5 \times 10^6$—*i.e.*, 1·5 multiplied by one million,

viz., 1,500,000. We shall constantly be using this abbreviation to save writing out large numbers.

Another abbreviation for very small numbers. The number 0·000005 means 5 divided by one million (1,000,000). We could write this another way, viz. $\frac{5}{1000000}$, but this is even more awkward than 0·000005. We have just used 10^6 as a shorthand for 1,000,000: let us use it again and write $\frac{5}{10^6}$. This is quite brief, but the mathematician does not even use the fraction line; he brings the 10^6 into the top line or numerator, and in order to distinguish it from 5×10^6 (which is 5,000,000) he places a — sign in front of the index, thus $0{\cdot}000005 = 5 \times 10^{-6}$.

(*Note.*—The expression 10^8 put into words is spoken this way: "ten to the eighth," or "ten to the eighth power." Similarly, 5×10^{-6} is "five times ten to the minus six.")

Kilocycles.—Most readers are aware that we often refer to wireless signals by their frequency as well as by their wave-length. Thus the London Regional or "Home Service" station has a frequency of 877,000 cycles per second, and also a wavelength of 342.1 metres. Instead of saying, 877,000 cycles per second we can use the term "kilocycles per second." The prefix "kilo-" means "thousands of," thus 877 kilocycles per second means 877 thousands of cycles per second. The abbreviation kc/s. is used for kilocycles per second. The term "kilo-hertz" is often used for the whole phrase "kilocycles per second," one hertz being one cycle per second. The abbreviation for this is kh.

Wireless Waves

What is a wireless wave? At the transmitter the transmitting circuit is connected to the aerial. One of the properties of an aerial is that it causes some of the alternating current, which passes to it from the transmitting circuit, to be converted into wireless waves. The well-known analogy of a stone dropped into a pool of water and producing ripples on the surface of the water gives a useful idea of what a wave might look like if only it were visible to the human eye. The waves are actually set up by the very rapid to-and-fro motions of the electrons which constitute the current in the aerial. They surge backwards and forwards at the frequency of the current and the waves are sent out—or RADIATED—in all directions.

(Special aerials, such as those used at the Post Office Beam Stations or for Radar, concentrate the waves in a beam and in these cases radiation occurs in one direction only.)

The waves travel outwards at a very high speed, in fact they travel at the speed of light, viz.: 186,000 miles per second. Thus in $\frac{1}{10}$th of a second the waves travel $\frac{1}{10}$th of 186,000 miles, *i.e.*, 18,600 miles, or nearly round the earth. When we calculate the wavelength of a broadcasting station, we always give the answer in *metres* and so we must convert the speed (the mathematician uses the term VELOCITY in place of speed) from *miles per second* into *metres per second*. We find that the velocity works out to 300,000,000 metres per second, which we shall write as 300×10^6 metres per second (1 mile = 1609·3 metres). We could write this velocity as 3×10^8 metres per second, but we shall find that writing it as 300×10^6 metres per second will simplify calculation.

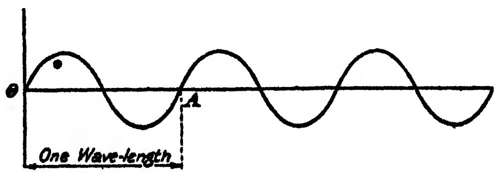
The waves must travel on something. It requires a very big stretch of the imagination to suppose that the waves can pass from the transmitter to the receiver without a something (called a MEDIUM) on which to travel, and although mathematicians can imagine a "nothingness" on which waves may "travel" we shall suppose that they travel on a medium called the ETHER. We cannot see or feel this ether, in fact we are only aware of it by means of such indirect effects as listening to a wireless programme. We assume that, whatever it is, it enables wireless waves (and light waves, X-rays, and other waves of a similar type) to travel from one place to another at the enormous velocity of 186,000 miles per second, or 300×10^6 metres per second.

Wavelength

One wave is formed each time the electrons in the transmitting aerial go through a complete cycle of alternation. Thus the number of waves created in one second is equal to the frequency of the current in the aerial. In two seconds twice this number of waves is created, and so on. We can make a diagram

FIG. 1.—THIS DIAGRAM SHOWS THREE COMPLETE WAVES.

One wave is formed each time the electrons in the transmitting aerial go through a complete cycle of alternation.



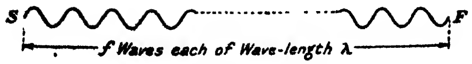


FIG. 2. — DIAGRAM SHOWING VELOCITY OF WAVES.

representing a wireless wave—or one part of it—and Fig. 1 shows three complete waves. The shape of each wave is similar to the shape of the alternating current graphs with which we are already acquainted, and a sine wave equation represents the wave; as before, it is known by the name sine wave, and the mathematician uses the same terms in referring to this wave as he uses for the alternating current wave. The length from O to A, along the axis, is called a WAVELENGTH and the symbol used for wavelength is the Greek letter "λ" pronounced "*lambda*."

Velocity of the Waves

Now the velocity of the waves is the distance that a wave travels in one second, and in one second there are as many complete waves produced as the number of complete cycles (*i.e.*, the frequency) of the current in the aerial. If each wave is λ metres long, then $\lambda \times$ (the number of waves in one second) is the distance the first wave has travelled in a second—*i.e.*, the velocity. In Fig. 2, S is a source of waves, each of wavelength λ, there being f waves produced per second. F is the point reached by one particular wave one second after it left the source. Thus the distance SF is occupied by f waves each of length λ, *i.e.*, SF $= f \times \lambda$. Therefore the velocity of the waves is $f \times \lambda$ metres in each second.

i.e., Velocity (V) = Frequency (f) $\times$ Wavelength (λ).
i.e., V (metres per sec.) $= f$ (cycles per sec.) $\times$ λ (metres)
or $$V = f\lambda \qquad (1)$$

Converting Wavelength into Frequency

The f of equation (1) is the frequency of the wireless signal to which we have already referred. Equation (1) shows us how to convert from wavelengths into frequencies, and *vice versa*, because the frequency multiplied by the wavelength is always equal to 300×10^6. (Whatever the wavelength the waves always travel at the same velocity.)

Example.—Suppose that we wish to convert a wavelength of 600 metres into frequency, we have:—

V (metres per sec.) $= f$ (cycles per sec.) $\times$ λ (metres), and

writing in the two values which we know, viz., V and λ, we have :—

$300 \times 10^6 = f$ (cycles per sec.) $\times$ 600 *i.e.*, 600 times f equals 300 times a million. It is quite easy to see that f equals half a million cycles per second.

i.e., f = 500,000 cycles per second.
or f = 500 kc/s., or 500 kh.

Using equation (1) we can draw up a table showing wavelengths in one column and the corresponding frequencies in a second column, thus :—

Wavelength (metres).	Frequency (kc./s)	Wavelength (metres).	Frequency (kc./s).
3,000	100	500	600
2,000	150	400	750
1,500	200	300	1,000
1,200	250	250	1,200
1,000	300	200	1,500
750	400	150	2,000
600	500	100	3,000

The table is incomplete, and in order to complete it we should have to enlarge it very considerably. Even if we increase the wavelengths by 1 metre at a time the table is still far from complete, and thus we must find a more convenient form of conversion chart.

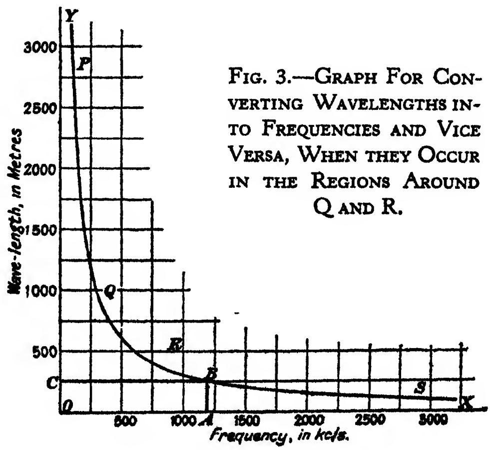


FIG. 3.—GRAPH FOR CONVERTING WAVELENGTHS INTO FREQUENCIES AND VICE VERSA, WHEN THEY OCCUR IN THE REGIONS AROUND Q AND R.

In Fig. 3, wavelengths are measured along OY, and frequencies along OX. The curved line PQRS represents all the points corresponding to the wavelength and frequency figures in the table, and it has the advantage that

intermediate values can be seen at a glance. As an example of the use of the graph let us convert the frequency of 1,200 kc/s. into a wavelength. The vertical line AB corresponds to the frequency we are converting, and it meets the curve PQRS at the point B. The horizontal line through B is BC, and this line corresponds to a wavelength of 250 metres. Thus we have converted from a frequency of 1,200 kc/s. to a wavelength of 250 metres.

The graph of Fig. 3 is most useful for converting wavelengths into frequencies, and *vice versa*, when these occur in the ranges corresponding to the regions around Q and R on the curve. In the regions around P and S the wavelengths and frequencies are so crowded together due to the oblique slope of the graph that it is very difficult to read values accurately. Can we remedy this so that the graph is equally clear for the whole of its length ?

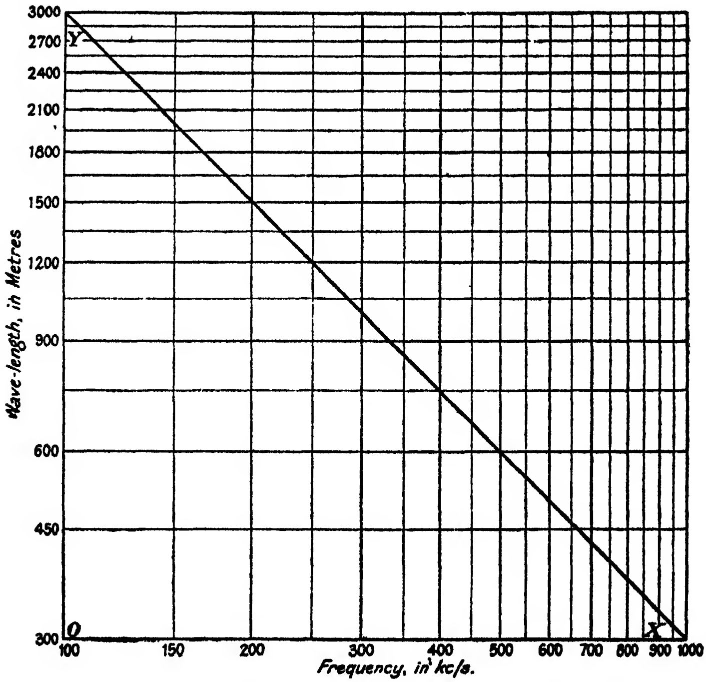


FIG. 4.—AN EXAMPLE OF A LOGARITHMIC GRAPH.

Here it will be seen that the graph is a straight line and it is now much easier to convert wavelengths into frequencies and *vice versa* at any part of the scale.

Look at Fig. 4. The graph is a straight line, but notice that the divisions along the axes OX and OY are not evenly spaced. Near to O the divisions are a big distance apart, and as the distance from O increases the intervals on the axes decrease. That is to say, the SCALE of values along both axes changes. In previous cases the scales have been regular—*i.e.*, the divisions equally spaced.

Logarithmic Scale.—The scale of Fig. 4 is called a LOGARITHMIC SCALE because the divisions along the axes correspond to the LOGARITHMS of the numbers instead of corresponding directly to the numbers themselves. Perhaps you do not know what a logarithm is? The logarithms of which we are speaking are a system of numbers which help us to calculate. They change difficult multiplication and division sums into simple addition and subtraction sums. We have no time or space here to discuss logarithms, and readers who cannot use a log. table should read the section on logarithms in a good arithmetic book, but further details on graphs and how to draw them will be found in the chapter on Resistances and Potentiometers.

The following table shows why the divisions on the axes of Fig. 4 are not evenly spaced. Column one is a list of actual numbers and column two gives the logarithms of these numbers. The numbers in column one increase regularly one at a time and correspond to the regularly spaced scale, but in column two they increase quickly at first and then more slowly and correspond to the logarithmically graded scale.

Number.	Logarithm of the Number.
1	0·0000
2	0·3010
3	0·4771
4	0·6021
5	0·6990
6	0·7782
7	0·8451
8	0·9031
9	0·9542
10	1·0000

Now look at the following table. What do you notice about it? Well, starting from 3 metres, which is equal to a frequency of 10^5 kc/s., as we *multiply* λ by 10, so we must *divide* f by 10.

λ (metres).	f (kc/s).
3	10^5
30	10^4
300	10^3
3,000	10^2
30,000	10^1 (= 10)

Fig. 4 is a conversion chart for wavelengths lying in the range from 300 to 3,000 metres. Suppose that we wish to convert a wavelength lying in some other part of the wavelength scale, do we require a separate chart? The advantage of the logarithmic scale is that we can use the one graph. All we have to do is to multiply or divide the wavelength or frequency by 10 as many times as necessary in order to bring it within the wavelength or frequency range of the graph, and then to multiply or divide the corresponding value, read from the graph, by 10 for the same number of times.

THE PROPAGATION OF RADIO WAVES

We have already mentioned that radio waves are assumed to travel in a medium known as the ether, and it is generally acknowledged that the man who first started to think constructively about this subject was Clark Maxwell.

He lived towards the end of the last century and his world was, of course, vastly different from the world of to-day. There were no motor cars, no telephones, radio valves, aeroplanes, and even insulated copper wires were not available to him; possibly he would not have used them if they had been, as he was a thinker rather than a practical experimenter. He sat in an arm-chair, probably gazing at the ceiling, allowing his tea to grow cold beside him, and he thought about the way things were happening to such good purpose that he evolved a theory

explaining how energy, present in one place, could leap across apparently empty space to manifest itself at a distance. The explanation which he advanced for this phenomenon, which could be observed by anyone feeling the warmth of the sun or observing the stars on a clear night, was that the energy was conveyed by means of wave motion.

The mathematical formulæ which he employed were very complicated and it is only given to a few people to understand them; these few have not challenged the accuracy of his conclusions and they consequently hold to-day. One of the main conclusions of his theories was the relation between wavelength, frequency and velocity which we discussed earlier in the chapter.

The next experimenter to leave his mark upon the progress of the science of radio was Hertz. He found that if he placed a ring of wire with a gap in it near to a spark coil, shown diagrammatically in Fig. 5, tiny sparks could be observed in the gap in the ring when the spark coil was operating. It was evident from this experiment that energy had been transferred from the spark coils to the ring of wire, and these two simple pieces of laboratory equipment were, in fact, the first radio transmitter and receiver. The effect which Hertz had discovered remained for many years a laboratory experiment. From the dimensions of his equipment, it is evident that the wavelength of the waves he was generating were what we should now call short or ultra short waves.

The direction which later development took, however, was to increase the wavelength employed. This is done by increasing the inductance and capacity of the oscillatory circuits associated with the transmitter and using similarly loaded circuits in the receiver. To secure radiation of energy from the transmitting circuits, these were coupled to a raised aerial wire at the transmitting end. At the receiving end, a similar raised aerial wire was used which picked up the energy radiated

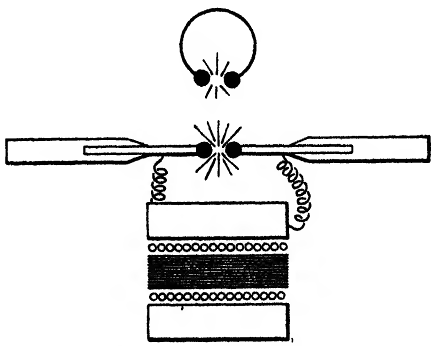


FIG. 5.—HERTZ TRANSMITTER AND RECEIVER.

from the transmitter at much greater distances than had hitherto been possible. By this means Marconi and other experimenters during the early part of the present century were able to increase the range of a few feet achieved by Hertz up to many miles, and before the 1914 war two-way communication was established across the Atlantic Ocean.

Having got hold of the idea that bigger aerials and longer waves (necessarily associated with lower frequencies) resulted in greater range and more reliable transmission, communications engineers built larger and larger wireless telegraph stations, as they were then called, and wavelengths were increased up to a maximum of about 30,000 metres.

Effect of Amateur Experimenting

After 1918 many amateur experimenters made their appearance, and as the British Post Office at that time thought that short waves were only useful for very short distance communication, say over a few miles, they allowed these amateurs to operate on wavelengths below those used for commercial purposes, the actual wavelengths allotted being from very slightly below to slightly above 200 metres. To ensure that they should not establish communication over any great distance, the power that they were allowed to use was limited to 10 watts.

The enthusiasm of the amateurs was not, however, in the least damped by these restrictions, and thousands of them set up their transmitting and receiving equipments, and it soon became apparent that, even with these low powers, very much greater ranges were being attained than were intended when the original concessions were made by the Post Office. They had been given a sprat to play with and it had grown into a very fine mackerel. Soon amateurs were constantly reporting reception across the Atlantic with their little 10 watt transmitters. In fact, the extraordinary ranges which were obtained by amateurs (and professionals) at this time caused a great deal of perplexity among scientists as these results did not really fit in with their propagation theories. Hitherto it had been thought that radio waves travelled outwards from the transmitting aerial in straight lines and, consequently, at some short distance from the transmitter, say 20 or 30 miles, these waves

would begin to leave the surface of the earth owing to the earth's curvature.

In order to get the waves to cling round the curving surface, it was thought that the solution was to increase the wavelength, the longer waves, as it were, taking the curve and any small excrescences on it, such as hills, in their stride. The greater range obtained by the long wave transmitters of the Post Office and the Marconi Company was put forward as evidence in support of this theory.

Amateur experimenters obtained such great ranges, however, on "Short" waves that scientists were forced to take notice of these results and put forward some explanation of them. One fact stood out and that was that the greatest ranges were obtained at night. Probably the reason the amateurs discovered this was that they *were* amateurs and thus pursued their hobby at night, sometimes working all night in their enthusiasm. Scientists, therefore, advanced a theory that the sun's rays had some effect on the conducting properties of the atmosphere, rendering the passage of waves through the atmosphere more difficult during the hours of daylight. The explanation which was finally accepted for the very long ranges obtained with very low powers was that there was a layer of reflecting gas in the upper atmosphere which acted as a sort of mirror, bending the waves down again to earth and preventing them from flying off into space.

Reflection of Waves

As we know from our observations of physics, light waves or heat waves are reflected from bright metallic surfaces which are themselves conductors of electricity. It would, therefore, seem reasonable to expect that any surface capable of reflecting electromagnetic waves would be itself a conductor of electricity. Now, at the surface of the earth the atmospheric air is not generally deemed a conductor of electricity; in fact, to obtain a discharge across a gap of air of even only 1/200th of an inch requires a pressure of 1,000 volts. If, however, we rarify the air, as we do when we form a vacuum or a partial vacuum, we then find that the air is much more conducting and quite small voltages will cause currents to flow through it. Before the war, the mass of neon advertisement signs that could be seen were evidence of the commercial exploitation of this phenomenon.

The Heaviside Layer

Going back to radio and the upper atmosphere, we know that as we go higher and higher in the air it becomes more and more rarified, and it is reasonable to suppose that at great altitudes the air would become more conducting in the same way as it does in evacuated tubes. The explanation advanced for this increasing conductivity at greater degrees of rarification is that the molecules of the air divide into ions, that is into separate smaller particles which are conducting. The degree of ionization which occurs is thought to be to some extent influenced by rays reaching the " stratosphere " from the sun and possibly other heavenly bodies.

The theory which was put forward, in the light of this reasoning, to explain long distance reception was that radio transmitters sent out energy more or less promiscuously in every direction from the aerial. The radiation from the aerial which went out along the surface of the earth was named the " direct " ray, and this could be picked up in the immediate vicinity of the transmitter. Owing to the earth's curvature, this " direct " ray petered out, as it were, at a distance of some 100 to 200 miles. Other rays from the transmitter rising from the transmitting aerial at an angle of, say, 15 degrees or 20 degrees, would strike the underside of the Heaviside layer (as the conducting gas was called after its discoverer, Professor Oliver Heaviside) at some distance from the transmitter and be reflected down to earth again to be picked up at maybe 1,000 or 2,000 or more miles away.

Owing to this phenomenon, it was quite possible that a transmitter could be heard up to 100 miles or so and then not heard

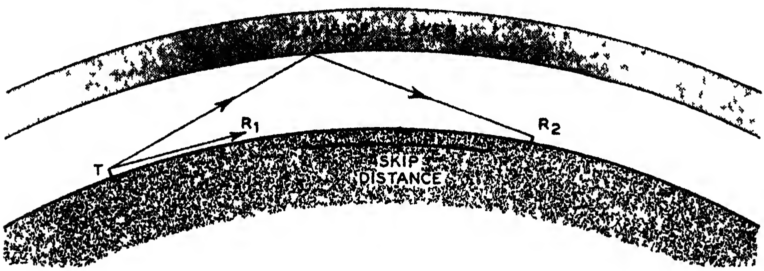


FIG 6.—HEAVISIDE LAYER REFLECTIONS.

at, say, 500 miles and then picked up again at much greater distances. The range at which it was not possible to pick up signals was often called the " skip " distance.

HOW RADIO IS BROADCAST

The early forms of wireless communication were telegraphic and made use of some form of code such as the International Morse Code. Spark transmitters, based on Hertz's experimental equipment, were employed and the messages sent out by means of interrupted spark discharges which set up oscillatory currents in the transmitting aerial. The resulting electromagnetic waves were discharged into the ether, picked up by the receiving aerial and re-converted into audible sound by the receiver.

Spark Transmitters

The basic circuit for a spark transmitter consists of a tapping key in series with a battery and the primary of an induction coil, the secondary of the coil being connected to a spark gap in series with the aerial and earth. By depressing the key, the circuit through the battery and the primary of the induction coil is completed and the resulting high-tension current induced in the secondary coil, (through the action of the coil make-and-break mechanism) causes a succession of sparks to jump across the gap. Corresponding oscillatory surges are set up in the aerial and electromagnetic waves are generated which will persist as long as the tapping key is depressed. A message can thus be transmitted in a series of dots and dashes by varying the time that the key is held down.

C.W. Transmission

With the introduction of the thermionic valve, the old spark gap transmitters have been superseded by the valve type, although the method of message transmission by signal interruption is still operated to some extent. In addition there is a system, known as " continuous wave " or C.W. transmission, in which the amplitude of the carrier wave is varied in accordance with the dots and dashes of the message it is required to transmit.

Telegraphy however is limited to the transmission of coded messages which need specialized interpretation and these systems are now used, mainly for shipping and aircraft navigational aids For the transmission of speech and music, a rather more complicated process is involved and general broadcasting and trans-ocean telephone services are carried out by means of radio telephony.

Radio-telephony

Briefly, with radio-telephony we convert sound waves into electrical impulses which are then superimposed on a carrier wave, the composite wave being fed to the transmitter aerial. The carrier wave acts as a conveyor belt and transports the electrical impulses to the aerial of the receiver, where the carrier wave is discarded and the electrical impulses are amplified and reconverted into sound waves by the loudspeaker. The story, however, is not quite so simple and must be considered in a little more detail.

Sound Waves

Earlier in this chapter, when we were referring to wireless waves, the ripple effect caused by dropping a stone into a pool was mentioned. Sounds are produced by air waves which behave in a similar manner. For instance, when a piano key is struck, the string will vibrate and cause the air round it to be compressed and rarefied alternatively. These air vibrations travel outwards in all directions, like the ripples on the surface of the pool and they have velocity, wavelength and amplitude similar to the wireless waves.

High notes cause a much faster vibration than low notes, in other words, the number of complete vibrations per second, or the frequency, of a high note is greater than that of a low note.

Many sounds are made up of a number of vibrations of different frequencies, for instance, when a gong is struck, a series of notes, high, low and intermediate are emitted at the same time and the resultant sound wave is fairly complicated.

The human voice covers an approximate frequency range of 100 to 4,000 cycles per second, and the human ear is sensitive to sounds of from 16 to approximately 10,000 cycles per second,

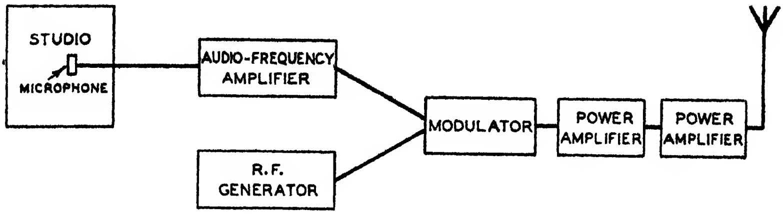


FIG. 7.—TYPICAL TRANSMITTER LAY-OUT.

but a frequency range of roughly 25 to 8,000 cycles per second gives a sufficiently natural reproduction of voice and music for most people.

Transmitter Lay-out

The general layout of a transmitter is illustrated diagrammatically in Fig. 7. It will be observed that the sequence of operations commences in the Studio, where the sound, say from an orchestra, produces a series of complex air waves which strike the diaphragm of the microphone.

The diaphragm is light and free to move, and, therefore, vibrates in accordance with the air waves striking it. The microphone converts these movements into a series of complicated electric currents having a mixture of frequencies within the range of the sounds being produced by the orchestra, i.e., between about 25 to 8,000 cycles per second. The electric currents from the microphone then pass through an amplifying stage to the modulator. There, they are superimposed on the radio-frequency current which is generated by a separate stage of the transmitter and the composite current is fed via the power amplifiers to the aerial, where the electromagnetic waves propagated have the wave-form of the composite or modulated radio-frequency current.

AMPLITUDE MODULATION

There are two methods of modulation at present in use, viz., amplitude modulation and frequency modulation. With the former, which is generally used for normal broadcasting purposes, the frequency of the carrier wave is kept constant and the amplitude varied as shown in Fig. 8 (a) and (c), the signal at (a) being

a fairly weak audio- (or sound) frequency signal, and that at (c) a much stronger audio-frequency signal. Actually the waveform is much more complicated, but for the sake of simplicity, a single audio-frequency signal is shown in the illustration. It should be clear, therefore, that the variations in volume of sound at the receiver are produced by variations in the depth of modulation of the carrier.

Sidebands

The modulated wave form can be regarded as being equivalent to three separate wavebands, i.e., if an audio-frequency wave of say 5,000 c.p.s. is superimposed on a carrier wave of frequency 1,000,000 c.p.s. (300 metres), the resultant wave is equal to three separate waves of frequencies, 1,000,000 c.p.s., 1,005,000 c.p.s., and 995,000 c.p.s. These latter waves are known as upper and lower sidebands.

Thus, to superimpose a musical frequency range of say from 25 c.p.s. to 8,000 c.p.s. on the 1,000,000 c.p.s. carrier, the upper sideband frequency range will be from 1,000,025 to 1,008,000 c.p.s. and the lower sideband from 992,000 to 999,975 c.p.s., producing a total band width of 16,000 c.p.s., which is double the maximum original audible frequency and more than double the original range of 7,775 c.p.s. (25–8000 c.p.s.).

This will indicate the necessity for some form of international control to limit the band widths of transmitters to reduce interference between stations working on adjacent wavelengths. A carrier frequency separation of 9,000 c.p.s. (9 kc/s) has been agreed upon which, if adhered to, has been found to be reasonably satisfactory from the point of view of inter-station interference, but it also has the adverse effect of reducing the range of audio-frequencies which can be transmitted.

FREQUENCY MODULATION

This system has been in use for some time in America, and is used in Service communications. It is not a different type of radio transmission, but merely one in which the signal has a different structure.

In a frequency modulated transmission, the radio-frequency carrier remains constant in amplitude but its frequency varies

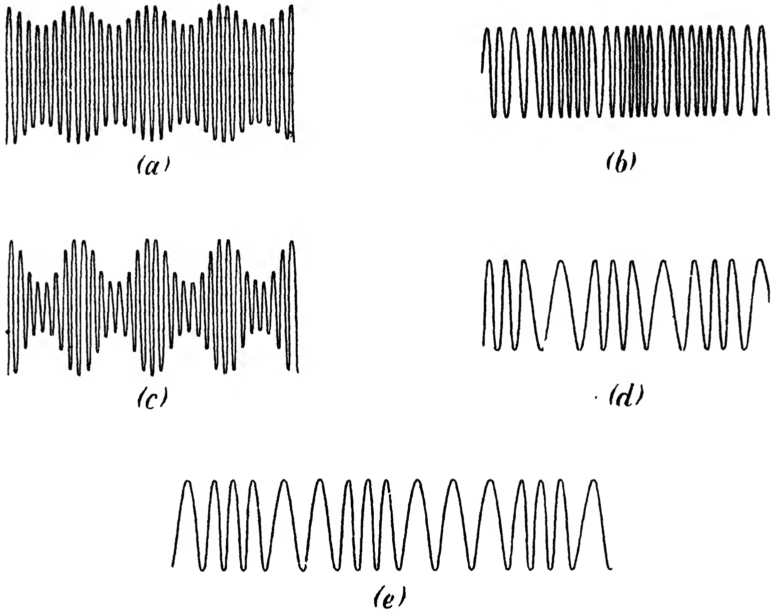


FIG. 8.—MODULATION.

(a) A.M. carrier. Low depth of modulation. (Weak A.F. note).
(c) A.M. carrier. Large depth of modulation. (Strong A.F. note.).
(b) F.M. carrier. Small deviation from mean frequency. (Weak A.F. note).
(d) F.M. carrier. Large deviation from mean frequency. (Strong A.F. note).
The L.F. component is of the same frequency in all these cases.
In (e) we have an F.M. carrier in which the A.F. component is of lower frequency chain (d).

about a mean value and the amount of variation about the mean is a measure of audio-frequency signal voltage. The rate at which the frequency deviation repeats is the frequency of the audio signal.

For example, as we have already mentioned in Fig. 8, (a) and (c) represent two amplitude modulated carriers of the type used in broadcast service. The audio-frequency or modulation component has the same frequency in both but the modulation in (c) is much deeper than in (a). (c) therefore, indicates a much stronger or louder signal than (d) though both are of the same pitch. In Fig. 8 (b) and (d) are the corresponding frequency modulated signals, again both having the same audio-frequency component but (d) being a stronger audio-frequency than (b). All these have the same audio-frequency component. Now look

at (e). This is a carrier of the same amplitude as (d) and it has the same variation in frequency since the waves widen out to approximately the same extent, but the frequency variation does not take place so often as in (d) the waves are not compressed together so many times in the same space and so this represents a F.M. carrier with a lower audio-frequency component than (d).

It is not difficult to see how a modulated frequency can be produced from speech currents Suppose we consider the simplest type of oscillator. If the capacity tuning of the circuit is altered, the resonance point will change and the oscillator frequency will change. Suppose a condenser microphone is included in the circuit, say across the inductance. Now when the microphone picks up speech, its capacitance will change and this will alter the oscillator frequency. Thus speech currents which vary in loudness are amplitude modulations and are converted into changes in oscillator frequency which are frequency modulations. Here we have the simplest (though not very practicable) form of frequency modulated transmitter.

Compared with the familiar amplitude modulated transmission, the band of frequencies required for F.M. is large, consequently it cannot be used in this country for ordinary broadcast bands where the carrier separation is limited to 9 kc/s. Some F.M. channels have band widths of 200 kc/s. This means that whereas A.M. transmissions are limited say to 5,000 cycles per sec., F.M. services may transmit audio frequencies up to say 16,000 c.ps.

For domestic broadcasting, F.M. is employed in America and the frequency band may be $\pm$ 75 kc/s. For narrow band communication, $\pm$ 30 kc/s. may be the maximum deviation. F.M. is very useful for short distance broadcasts or directional point to point communication systems.

The Receiver

The receiver of a F.M. system is more complicated and, therefore, more expensive than the normal A.M. receiver. In the design and assembly, precautions have to be taken similar to those employed for the modern ultra-short wave superheterodyne receivers and, in addition to the circuits normally associated with this type of receiver, two further stages are incorporated viz., the "limiter" and the "discriminator," which are quite different from any stage of an ordinary broadcast receiver.

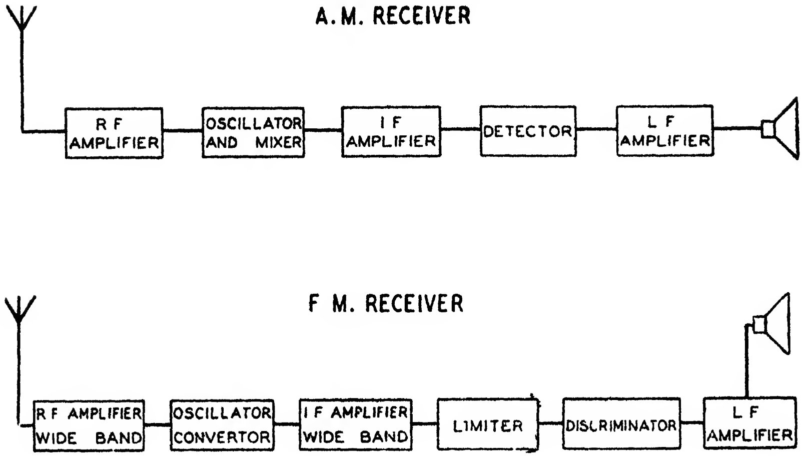


FIG. 9.—BLOCK DIAGRAMS OF A.M. AND F.M. RECEIVERS.

(*Top.*)—An ordinary broadcast (A.M.) receiver.
(*Bottom*).—A receiver for frequency modulation.

The radio-frequency and oscillator stages require to be of wide frequency tuning to accept the large number of sidebands involved. While ordinary A.M. transmissions comprise a carrier frequency and two sidebands, one on either side of the carrier, in F.M. transmissions a large number of sidebands are produced and their number increases as the ratio between the deviation and the audio frequency increases.

The function of the limiter is to ensure that the input to the discriminator is absolutely constant, i.e., the incoming signal is maintained at the same amplitude, the amplification of this stage being automatically decreased as the signal amplitude increases, and increased as the signal amplitude decreases. Any amplitude modulation is thus eliminated and as nearly all noise interference is a form of amplitude modulation, that, too, is effectively barred by the limiter stage. For the same reason, normal amplitude modulated transmissions cannot be received on F.M. equipment.

The frequency discriminator, acting as a frequency detector is thus supplied with a radio- or intermediate-frequency signal which is purely frequency modulated. This signal is converted by the discriminator into an amplitude modulated signal which is passed on to a diode rectifier.

Push-pull amplification is preferable for the output stage to

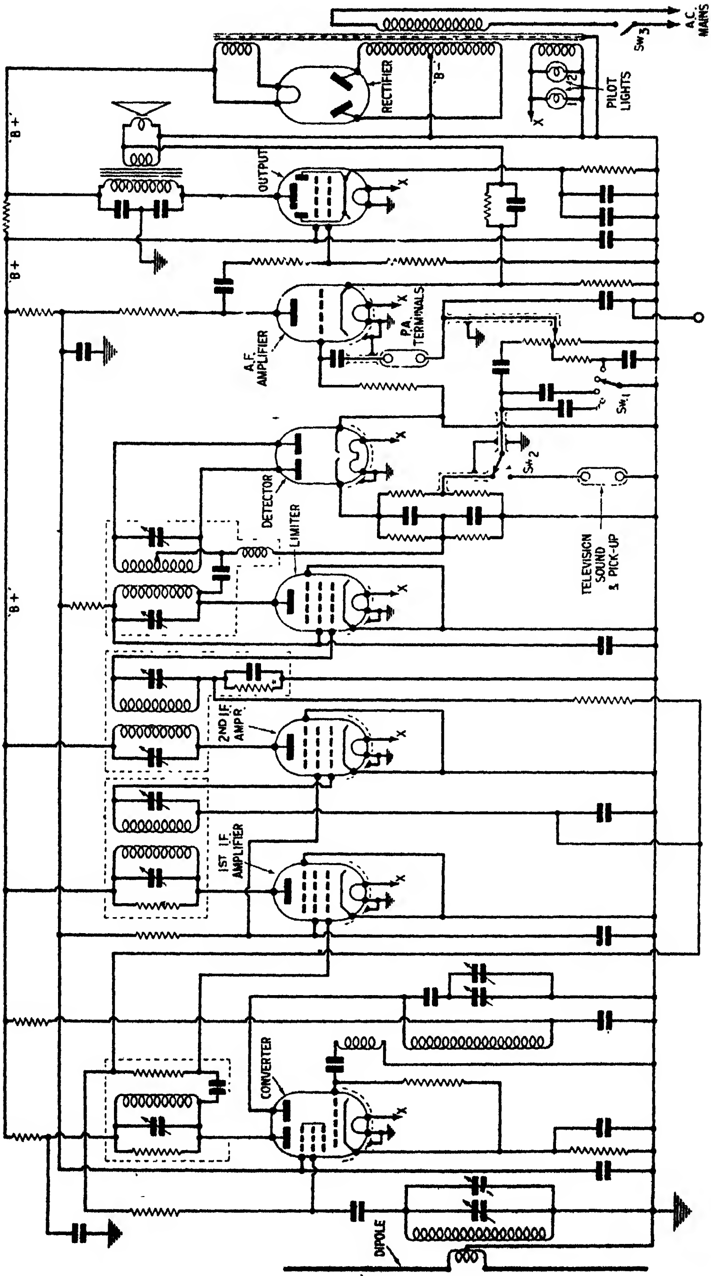


FIG. 10.—TYPICAL 8-VALVE CIRCUIT FOR F.M. RECEIVER.

achieve the highest possible standards of reproduction, otherwise the advantage of the wider audio-frequency range possible with F.M. would be lost.

The Aerial

The aerial system for a receiver consists of a half-wave dipole, usually fitted with a reflector. This type of aerial has been developed specially for ultra-short wave reception and the basic principles are dealt with in Chapter XXI.

Advantages and Disadvantages of F.M.

The chief advantages of F.M. are the much greater range between the lowest and highest audible power level which can be transmitted, the high fidelity of the reproduction and freedom from noise. In A.M. transmissions, a sudden large increase in audio-power may cause overmodulation and damage the modulator and/or R.F. amplifier unless corrected. In F.M. transmission, the effect is simply to produce a wide deviation in mean frequency. Static noise is largely an amplitude modulated form of disturbance and covers such a wide band of frequencies that it cannot be tuned out in the usual A.M. receiver.

Carrier noise, the rushing sound normally associated with A.M. reception when no music or voices are being transmitted, does not occur with F.M. transmission and the broadcast programme can be heard against a dead silent background.

Other advantages of F.M. are (1) Interference from other transmitters, including heterodyne, is reduced since a weaker carrier can modulate the desired carrier only at audible frequency. (2) If two F.M. stations work on the same channel, there will be negligible interference provided one is received at a level reasonably higher than the other.

The main disadvantage of the system is the limited optical range which is associated with all ultra-short wave transmitters and necessitates the erection of stations on specially selected sites located in the centre of the area to be served. In the case of a national F.M. network, many stations would be required and additional aerial systems would be necessary for alternative programmes. As the system is essentially directional, unless the aerials for the various programmes were grouped together, some form of rotatable aerial might be required at the receiver to achieve programme selection.

Tuning is more difficult than with the modern A.M. receiver which is normally fitted with some tuning indicating device, and reception is subject to distortion due to signals reaching the aerial from an indirect source such as by reflection from buildings or erections in the vicinity of the receiver aerial.

BROADCAST RELAY SYSTEMS

Rediffusion, or relay systems, provide a satisfactory means of affording broadcast service to people who live in areas where reception by the usual means is poor. As early as 1927, transmission of broadcast programmes over wires came into favour, and Relay Companies installed trunk and branch lines with tappings to listeners' receivers.

In some of the remotest parts of Britain, certain areas are screened by mountains which prevent satisfactory reception on the normal type of aerial. To overcome this difficulty, a central reception point is established at high level, with a very efficient aerial system and a local amplifier, after increasing the incoming signals by amplification, feeds out the programme over wire conductors to individual listeners.

This means of distribution has the advantage that the main receiver can be installed at a suitable point remote from any industrial area, so that reception free from local interference can be redistributed by suitable selection of the position of the main receiver.

The Aerial Amplifier

This unit is designed to cover a broad frequency band, so that transmissions of all wavelengths can be amplified to the same degree for passing on to the main receiver. The aerial amplifier is made of robust construction, suitable for outdoor unattended installation. It contains the necessary mains transformer, amplifier circuit and filter network to prevent high-frequency signals being injected into the mains system, as these signals would cause interference if distributed over the mains network.

Aerial Systems

To overcome the effects of fading, two aerial systems are sometimes used at slightly different locations and with different

directional properties. This method ensures that it will be most unlikely for minimum signal strength to occur in both systems at the same instant and effects of fading are largely counteracted. These two aerials feed two separate receivers, whose outputs are passed on to a mixer where they are combined as one train of signals to be passed on to the main amplifier.

Programme Selection

For the reception of the chief home stations, the reception units may have fixed tuning, one amplifier circuit being provided for each station and selective switching employed for changing over from one programme to another.

The original relay services carried audio-frequency signals for a single programme over a pair of wires to which a further pair were subsequently added, to give a second choice of programme to the listener. The requirement of further alternative programmes, without additional wiring, led to the adoption of the modulated carrier frequency systems. By this means almost any number of programmes can be sent out simultaneously.

One commercial system provides for six programmes as being the optimum number likely to receive attention from listeners. Four of these channels are occupied by existing B.B.C. transmissions, leaving two spare channels for future demands.

Distribution

The transmission line is of very simple construction, consisting of two insulated copper conductors carried by insulators supported by brackets affixed to the brickwork of the house. The reproducer unit is installed and connected to the system by a single cable. There are no tuning controls and programme choice is made by means of a selector switch.

Advantages of Relay Systems

Such systems, apart from those utilized in bad reception areas, have many advantages. The receiver equipment can be designed to include many refinements which improve reproduction and which could not, from price considerations, be incorporated into each listener's receiver.

The signal strength is high, with very low noise level, and is

substantially constant irrespective of distance from the transmitter. There is no interference with, or from, other services, and the carrier frequencies, unlike those of broadcast transmissions, can be chosen and again selected to give the most suitable positions in respect of each other. This results in the best reproduction with least possibility of interference.

CHAPTER VI

RESISTANCES AND POTENTIOMETERS

A RESISTANCE in electrical and wireless work is a device specially introduced into a circuit to oppose the flow of an electrical current. The unit of resistance is the ohm, which is that resistance which allows one ampere to flow when unit voltage is applied across it.

It is important to grasp these relationships and also to understand Ohm's Law and its application so that a correct value of resistance can be used in a circuit and, furthermore, that a suitable kind may be selected which will safely carry the required amount of current without overheating or burning out. The first section of this chapter is therefore devoted to a study of Ohm's Law and its graphical representation.

Ohm's Law sounds very imposing, but it is really quite a simple matter. Ohm found that the voltage across the ends of a wire carrying an electric current was always PROPORTIONAL to the current in the wire. What do we mean by "proportional"? Well, let us consider an actual example such as Ohm might have encountered during his experiments.

Suppose that we take a length of wire, a battery, a voltmeter, and an ammeter, and connect them together as shown in Fig. 1. B is the battery, the zig-zag line XY represents the wire, V is the voltmeter and A is the ammeter. Suppose that when the voltage reading of V is 10 volts, the reading of A is 2 amps. What will happen if we increase the voltage of the battery so that V's reading is twice 10 volts (= 20 volts)?

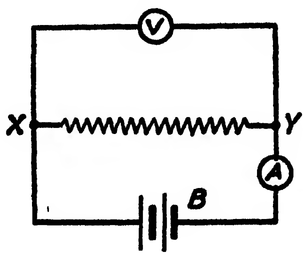


FIG. 1.—A SIMPLE EXPERIMENT TO ILLUSTRATE OHM'S LAW.

B is a battery, XY a length of wire, V a voltmeter, and A an ammeter.

Ohm found that when the voltage reading was doubled, the current reading was also doubled, and that when the voltage reading was multiplied by five, the current reading was also multiplied by five.

In fact, he found that by whatever number the voltage reading was multiplied or divided, the current reading was multiplied or divided by that same number, always provided that he used the same length of wire during the course of each experiment.

Now mathematics is really a shorthand notation; that is to say, it provides a quick way of expressing facts. When we state that "the voltage is proportional to the current," we are stating in a shorthand way the abiding results of a certain group of Ohm's experiments. But we can say this more briefly by replacing the words with letters. We use E for volts indicated by the voltmeter and I for amperes indicated by the ammeter. Then we shall have :—

E (volts) equals I (amps.) × R (a constant number, and which is actually equal to the resistance, in ohms, of the length of wire XY in Fig. 1),

$$\text{i.e., } E = I \times R$$
$$\text{or, Volts} = \text{Amps.} \times \text{Ohms.}$$

The piece of mathematical shorthand $E = I \times R$ is called an EQUATION, because it states that one thing, on the left-hand side of the = sign, is equal to some other thing on the right-hand side. We often have to deal with more than one equation in mathematical work, and so we number each equation (1), (2), (3), etc., for easy reference. You will have gathered already that the mathematician is really a lazy man who likes to find the shortest way of doing things. The equation which we have just set down will obviously be number (1), so :—

$$E = I \times R \quad . \quad . \quad . \quad (1)$$

We seldom use even the multiplying sign in mathematics, and instead of writing $I \times R$ we should write simply $I R$, so that we at last come to the shortest way the mathematician has of writing this equation which expresses Ohm's discovery, viz. :—

$$E = I R \quad . \quad . \quad . \quad (1)$$

Expressing this in words we have :—

"The voltage across the ends of a wire carrying an electric

current is equal to the current in the wire multiplied by the resistance of the wire."

How the Formula is used

Sometimes we refer to equation (1) as a FORMULA, and we use this word because we are thinking of the equation in a different sense from that previously. The equation is the mathematical statement of a relation, or connection, between the three factors represented by E, I, and R. If we know the value of two of these factors, we can predict the value of the third factor corresponding to the values of the first two.

Example 1.—Thus, consider the case of a valve which requires a filament voltage of 4 volts and takes a filament current of 0·25 amps. We are told the values of E and I, can we find the value of R? Well, we have our formula :—

$$\text{E (volts)} = \text{I (amps.)} \times \text{R (ohms)}.$$

Let us write the actual values in place of the mathematical shorthand ; we have :—

$$4 = 0{\cdot}25 \times \text{R (ohms)},$$

i.e., that 0·25 of R (ohms) equals 4 ; what is R ?

It is a simple step in arithmetic to see that

$$\text{R (ohms)} = \frac{4}{0{\cdot}25} = 16$$

so that the filament resistance is 16 ohms.

Example 2.—What is the voltage across the ends of a resistance of 3,500 ohms which is carrying a current of 15 milliamps. ?

Now, as before,

$$\text{E (volts)} = \text{I (amps.)} \times \text{R (ohms)}$$

and we must substitute the actual values for I and R, but we are given I in milliamps., and in our formula I is in amps. ; thus we must convert the 15 milliamps., into amps., which we can do if we remember that 1,000 milliamps. = 1 amp. Therefore 15 milliamps. = $\left(\frac{1}{1{,}000} \times 15\right)$ amps. Substituting the values in the formula, we have :—

$$\text{E (volts)} = \left(\frac{1}{1{,}000} \times 15\right) \times 3{,}500$$

and when we remove the brackets and work out the arithmetic we find the answer to be :—

$$\text{E (volts)} = 52{\cdot}5.$$

Similarly we could find the current flowing through a resistance when we know the value of the resistance and the voltage across its ends.

Charts and Graphs

An equation, or formula, is very useful for solving problems, but the engineer and the experimenter cannot always spare the time necessary for working out their problems in this way. They prefer to use CHARTS and DIAGRAMS (GRAPHS) in which all their problems are already worked out, so that they need only refer to the appropriate answer. Let us suppose that we are going to use a resistance of, say, 5,000 ohms in a circuit in which the current can be varied between 0 and 100 milliamps., and we want to know the voltage across the ends of the resistance for each value of current. Equation (1) tells us that the voltage is proportional to the current, so that if we work out the voltage for one particular value of current we can make a table showing the voltage at any current value. We may choose any convenient current value for our calculation, and 10 milliamps. is an easy value to work with. We have :—

$$E \text{ (volts)} = I \text{ (amps.)} \times R \text{ (ohms)}$$

and 10 mA. $= \dfrac{10}{1{,}000}$ amps. then E (volts) $= \dfrac{10}{1{,}000} \times 5{,}000$

i.e., E (volts) = 50.

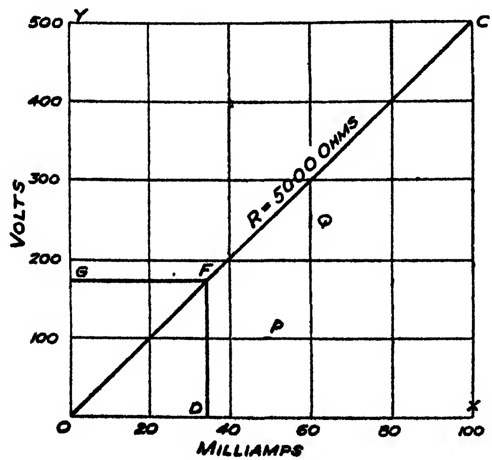


FIG. 2.—A SIMPLE GRAPH.

Marks are made along two of the ruled lines OX and OY. The marks along OX correspond to the values of current, and those along OY to value of voltages. Thus every vertical line corresponds to some particular value of current, and every horizontal line to a particular value of voltage.

Now the voltage is directly proportional to the current, so that at 1 milliamp. $\left(=\frac{10}{10}\right)$ the voltage will be $\frac{50}{10}$ volts = 5 volts. Similarly at 50 milliamps. (= 10 × 5) it will be 50 × 5 volts = 250 volts, and our table will be like this :—

Current (milliamps).	Voltage (volts.).	Current (milliamps.).	Voltage (volts).
1	5	10	50
2	10	20	100
3	15	30	150
4	20	40	200
5	25	50	250
6	30	60	300
7	35	70	350
8	40	80	400
9	45	90	450
		100	500

We should have to make a new table for each value of resistance we are using, and, moreover, the table is not really complete because it does not give the voltages corresponding to the intermediate fractional values of current, such as, for instance, $5\frac{1}{2}$ and $21\frac{3}{4}$ milliamps. We could calculate these intermediate values and include them in the table, but it would not be long before the table became very cumbersome.

We could, of course, find our intermediate values in this way: suppose we wish to find the voltage value corresponding to $5\frac{1}{2}$ milliamps. From the table we see that 5 milliamps. produce a voltage across the resistance of 25 volts, and 6 milliamps. produce 30 volts. Therefore a current of $5\frac{1}{2}$ milliamps., which is half-way between 5 and 6 milliamps., corresponds to $27\frac{1}{2}$ volts, which is half-way between 25 and 30 volts.

In this particular instance this process of calculation (which the mathematician calls INTERPOLATION) produces the correct answer, but in the majority of cases, where we have to deal with tables drawn up from more complicated formulæ, this method will not give a strictly accurate answer, although it generally gives an answer which is *nearly correct*, and which the mathematician calls an APPROXIMATION.

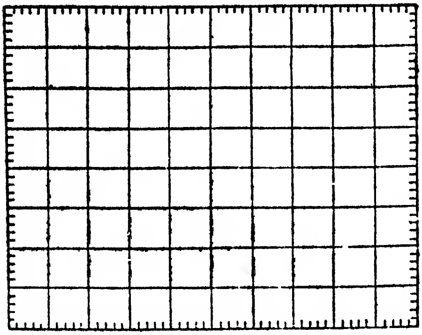


FIG. 3.—MAKING A SIMPLE GRAPH.

We are going to plot a graph showing the relation between resistance and length of a No. 30 S.W.G. copper wire. First obtain a sheet of squared paper of a convenient size. The best type of paper to use has every fifth or tenth line emphasized with the smaller squares shown faintly. In the illustration the smaller squares have been omitted.

This additional calculation also takes a certain amount of time, however, and there is another easy way of representing these corresponding values of current and voltage, and that is by means of a diagram or graph.

The graph is drawn on "squared paper"—*i.e.*, paper on which lines are ruled in two directions so as to produce a pattern of squares. Fig. 2 shows such a diagram.

For the benefit of those who are unfamiliar with the process of plotting a graph, detailed instructions are given in the following paras., together with a series of diagrams showing every step in the construction. Once the details have been grasped the reader will find it an easy matter to construct graphs for any two quantities which vary with respect to each other.

How to make a Graph

Whenever you buy a valve, you will find inside the carton a

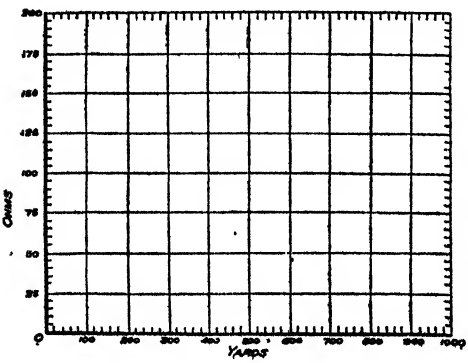


FIG. 4.—MAKING A SIMPLE GRAPH.

The next point is to obtain from a table a number of corresponding values of resistance and length for this type of wire. Next mark the horizontal and vertical scale on the graph paper to agree with the maximum values of resistance and length. In the present case, the highest values are 200 ohms and 1,000 yards respectively.

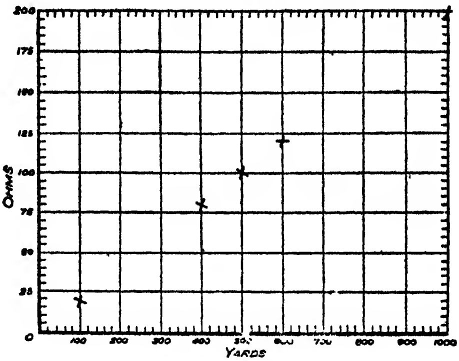


FIG. 5.—MAKING A SIMPLE GRAPH.

Now plot on the graph a few points which have been obtained from the table. The points plotted here are the following: 200 ohms, 1,000 yards; 120 ohms, 600 yards; 100 ohms, 500 yards; 80 ohms, 400 yards; 20 ohms, 100 yards.

graph showing the characteristics of the valve. The following notes show how these graphs are constructed.

The resistance of a length of wire is proportional to its length. For example:

If 1,000 yards of No. 30 S.W.G. copper wire have a resistance of 200 ohms; 500 yards have a resistance of 100 ohms; 100 yards have a resistance of 20 ohms, etc.

Now take a sheet of squared paper.

Mark on it two scales, one for resistance and one for length. Arrange each scale as far as possible so that it will occupy all the space available. For example, in the present instance the scale of length should be from 0 to 1,000 yards and the scale of resistance from 0 to 200 ohms.

The chief art in drawing a graph is to fix the scales so as to make the best use of the space available. The next stage is to mark on the graph paper points corresponding to the values of resistance and length. This stage is shown in Fig. 5.

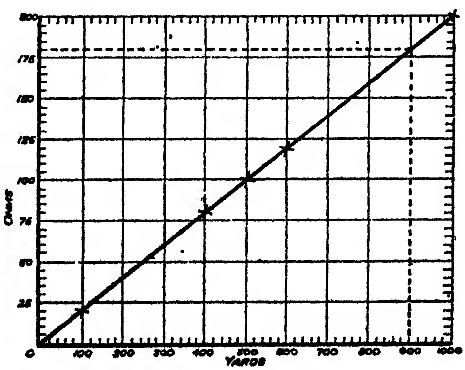


FIG. 6.—MAKING A SIMPLE GRAPH.

Now join the plotted points by means of a smooth line or curve. In the present case, all the points can be joined by a straight line. The chart is now completed and can be used for reading off any intermediate values desired. For instance, it can be seen that 900 yards have a resistance of 180 ohms.

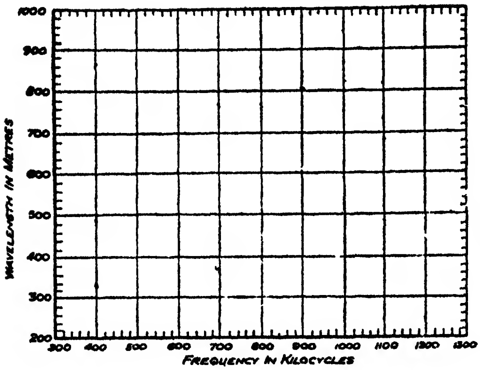


Fig. 7.—Wavelength and Frequency Chart.

Here again the scales must first be decided upon to suit the limits of the two variables which are to be plotted.

Now join the dots by a smooth line or curve. The graph so formed is shown in the next illustration, and from it you can read off the resistance corresponding to any length of the wire from 0 to 1,000 yards. This is, of course, a very simple example, but even in this case it can be seen that this graph takes the place of a table containing hundreds of entries. Now try another case, Wavelengths in Metres and Frequency in Kilocycles.

Prepare the chart as before, making the scales to suit the values which have to be charted. Next plot the points corresponding to a few selected values. This has been done in Fig. 8.

In this case, the points do not lie on a straight line so that a smooth curve must be drawn to take in all the points. This curve enables you to read off the wavelength corresponding to any given frequency or the frequency corresponding to any given wavelength between the limits of the chart (Fig. 9).

Advantages of Graphs

There are two great advantages in the use of graphs as compared with tables. First, a graph shows at a glance how one quantity alters when another quantity is varied. Secondly, a graph enables corresponding values of two variable quantities to be read off at a glance. For instance, the valve characteristic curves found in every valve carton show at a glance how the plate current varies according to the grid voltage so that the set designer can readily select the most suitable grid bias to use to obtain the results required.

In many cases, such as the valve curves just mentioned,

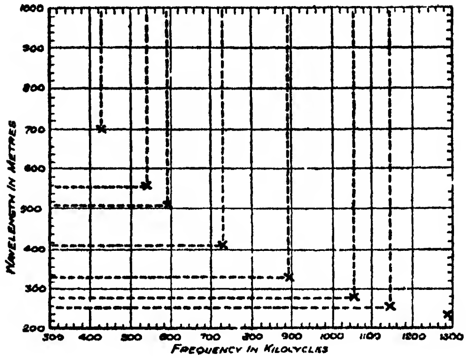


FIG. 8.—WAVELENGTH AND FREQUENCY CHART.

After the scales have been fixed a number of points taken from a wavelength-frequency table are plotted as shown.

the charts are not prepared from tables, but are plotted as a result of actual experiments. Apparatus is included to enable the corresponding readings to be taken of the two variables. These are recorded and afterwards plotted in graph form.

Every vertical line in Fig. 2 corresponds to some particular value of current, and every horizontal line to a particular value of voltage.

For instance, the point P is on the vertical line representing 50 milliamps., and on the horizontal line representing 100 volts. Similarly, Q corresponds to values of 60 milliamps. and 250 volts. The intersection of each pair of vertical and horizontal lines corresponds to one value of current and to one value of voltage. The line OC passes through all the points corresponding to the values in the table and thus it represents our 5,000 ohms resistance, and it enables us to find the voltage across the ends of the resistance at any current value shown along the line OX, and *vice versa*. Let us check this. From the table the voltage produced by a current of 35 milliamps. is 175 volts. On the graph DF is the line representing 35 milliamps., and it meets

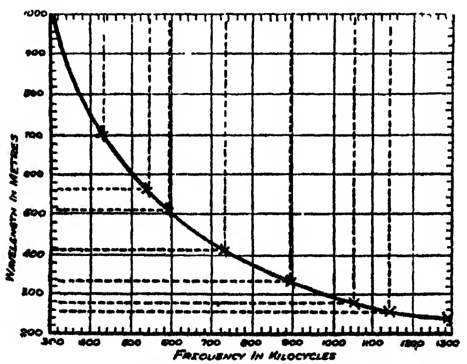


FIG. 9.—WAVELENGTH AND FREQUENCY CHART, COMPLETED

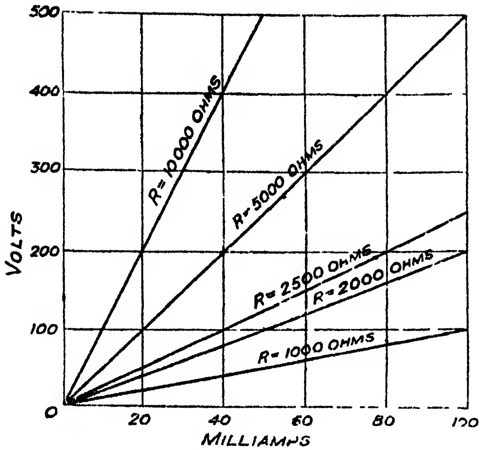


FIG. 10.—THIS SHOWS A CHART DRAWN FOR RESISTANCE VALUES OF 1,000, 2,000, 2,500, 5,000 AND 10,000 OHMS.

OC at F. The horizontal line GF through F corresponds to 175 volts. The reader will be able to check other pairs of values for himself.

In addition to the fact that this graph is much more compact than the table, and that it gives every intermediate value of current, it possesses another advantage. Other lines, corresponding to different values of resistance, can be drawn on the one graph, and Fig. 10 shows such a chart drawn for resistance values of 1,000, 2,000, 2,500, 5,000, and 10,000 ohms. Each line was found by calculating some of the current and voltage values, as previously, for each resistance, and the points were joined to form the lines.

Whatever value of resistance we use, we shall always find that this graph is a straight line. It is the graph which represents our equation (1) when R is fixed at a particular value. E and I are both variable, and we have one variable in the numerator on each side of the equation. Such an equation always forms a graph which is a straight line.

Voltage Drop Calculations

In practice, Ohm's Law calculations are employed principally to determine the value of resistance required to give a specified " voltage drop."

For instance, let us suppose that in the circuit of Fig. 30, on page 170, the anode of the S.G. valve requires a voltage of 120, and at that voltage the valve passes an anode current of 4 milliamperes. Now the H.T. voltage supplied by the mains equipment is 250, so it is required to " drop " 130 volts across resistance R6. What must be the value of R6? Easy, if we use our previous formula, R = E/I. It is 130/4 milliamps., or

$\frac{130}{1} \times \frac{1,000}{4}$, which equals $\frac{130,000}{4}$, or 32,500 ohms. In practice, we should choose either a 30,000 ohm or 35,000 ohm component, whichever was more convenient.

Power Rating

Before we can decide on the type of resistance required, we must know how much power, in watts, it will have to deal with. The power is equal to the number of volts "dropped," multiplied by the number of amperes passing, so in this case it is equal to $130 \times \frac{4}{1,000,}$ or 520/1,000, which is approximately half a watt.

The wattage can also be calculated when only the current and resistance are known; it is found by substituting in the formula: power (in watts) equals the square of the current multiplied by the resistance, or:—

$$W = I^2R \ldots\ldots\ldots (2).$$

As an example we will suppose that when a 10,000 ohm voltage dropping resistance has been inserted in a high-tension feed circuit, the current flowing is 8 milliamps. By substitution in our new formula $W = I^2R$, we get $W = \left(\frac{8}{1,000}\right)^2 \times 10,000$, which can be simplified to $\frac{64}{1,000,000} \times \frac{10,000,}{1}$ and by cancellation this gives us the result of $\frac{64}{100}$ which is approximately 2/3 (of a watt).

Series and Parallel Connections

The examples given up to now have dealt only with single resistances; it is often necessary to have a network of resistances, which may be connected in series, in parallel or a combination of both, known as series-parallel.

Series Connection.—If a number of resistances R_1, R_2, R_3 . . . are connected together in series, the same current I will pass through all resistances, and E (the total voltage drop) $= E_1 + E_2 + E_3 \ldots$ (the sum of the voltage drops across each resistance)—

$\therefore E = E_1 + E_2 + E_3 \ldots = I(R_1 + R_2 + R_3 \ldots) = IR$, where R = total resistance.

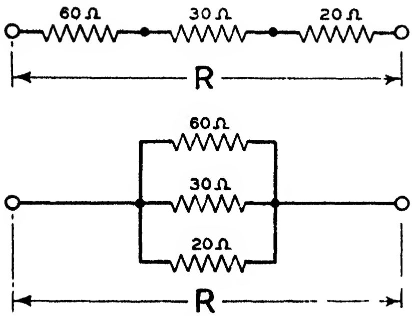


FIG 11.—RESISTANCES IN SERIES AND IN PARALLEL

Therefore $R = R_1 + R_2 + R_3 \ldots$

Parallel Connections.—In this case the same voltage drop, E or potential difference, is applied across each resistance. The currents are $I_1 = \frac{E}{R_1}$, $I_2 = \frac{E}{R_2}$, $I_3 = \frac{E}{R_3}$, etc., and the total current is $I = E\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots\right) = \frac{E}{R}$, so that the combined resistance is obtained from the formula:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

In the case of two resistances only, this can be simplified to :

$$R = \frac{R_1 R_2}{(R_1 + R_2)}$$

As an example, let us consider the three resistances in Fig. 11 of 60, 30 and 20 ohms. Their series combination gives $R = 60 + 30 + 20 = 110$ ohms.

In parallel :

$$\frac{1}{R} = \frac{1}{60} + \frac{1}{30} + \frac{1}{20} = \frac{1 + 2 + 3}{60} = \frac{6}{60} = \frac{1}{10}$$

So that R = 10 ohms. The parallel sum of resistances must always be less than the value of the smallest resistance.

Series-Parallel Connections

This combination is illustrated in Fig. 12 and is solved by first finding the effective resistance of all parallel combinations by the parallel rule, so as to get finally a set of resistances in series, which are simply added together.

Referring to Fig. 12, we first deal with the parallel resistances 9 and 18 ohms. These combine to give

$$R = \frac{9 \times 18}{(9 + 18)} = \frac{162}{27} = 6 \text{ ohms.}$$

The parallel combination of 48, 48, 12 and 8 ohms gives :

$$\frac{1}{R} = \frac{1}{48} + \frac{1}{48} + \frac{1}{12} + \frac{1}{8} = \frac{1 + 1 + 4 + 6}{48} = \frac{12}{48} = \frac{1}{4}$$

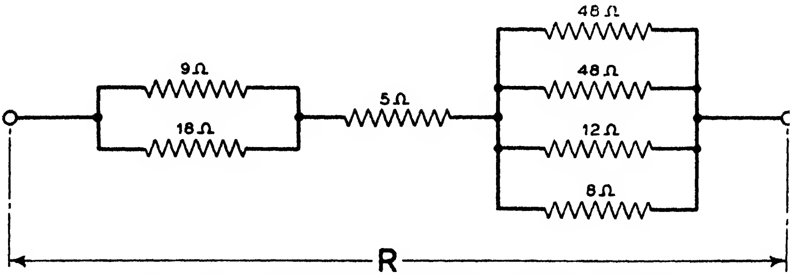


FIG. 12.—RESISTANCES CONNECTED IN SERIES PARALLEL.

so that R = 4 ohms. Thus, we now have 6, 5 and 4 ohms in series giving an overall total of 15 ohms.

Suppose a P.D. of 180 volts is applied across the ends of the combination. The current from the source will be 180/15 = 12 amps.

If we wish to find the current distribution in the various branches, in the first place we find the voltages across the three sections, employing Ohms' Law again. For the 9 and 18 ohms parallel combination which gives the effect of 6 ohms, it will be $6 \times 12 = 72$ volts. The current in the 9 ohms resistance is, therefore, $72/9 = 8$ amps; in the 18 ohms resistance it is $72/18 = 4$ amps. Thus it will be noted that the two currents add up to the already calculated 12 amps.

For the right-hand combination the P.D. is $12 \times 4 = 48$ volts and the currents are therefore $48/48 = 1$ amp, $48/48 = 1$ amp, $48/12 = 4$ amp. and $48/8 = 6$ amp. Again, the total current is $1 + 1 + 4 + 6 = 12$ amps.

The power dissipation can also be found. As we have already mentioned, it is I^2R or EI for each resistance. Thus for the 9 ohms resistance, it is $8^2 \times 9 = 576$ watts, or $72 \times 8 = 576$ watts. The rating of the others can be similarly found.

Types of Resistances

The nature, value and form of the resistance are determined by its purpose. The simplest form consists of a coil of wire made from a metal or alloy that possesses a high degree of resistivity; others consist of carbon or metallic compositions of various sorts enclosed in a carton of some kind with metal contacts or connecting wires at each end.

The resistivity of a metal is compared to that of silver, which is taken as 1; soft iron is seven and a half times as high; German

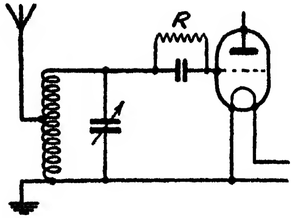


Fig. 13.—Grid Leak in Simple Valve Set.

The resistance R is shunted across the grid condenser. It may have a value of about 2 megohms.

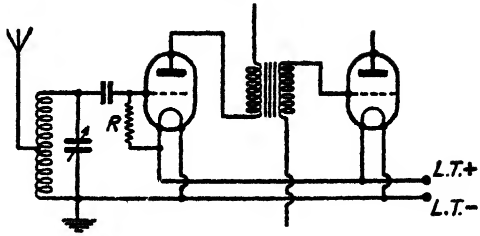


Fig. 14. –Grid Leak in Two-Valve Set.

When the first valve is the detector and is followed by L.F. stages, the grid leak R is connected between grid and low-tension positive.

silver eighteen times ; some alloys of hard steel are twenty-one times higher than that of silver.

Nickel-chrome steel is extensively used for wire-wound resistances on account of its strength and electrical properties.

APPLICATIONS OF RESISTANCES

The Grid Leak

One of the simplest but most important applications of a resistance in a wireless set is that used in the grid circuit of a detector valve and generally known as a grid leak.

These are usually of the composition type in small sets, and may have values of from ½ to 5 megohms.

In the case of a single valve receiver, the grid leak is shunted across the grid condenser, as in Fig. 13, but when the first valve is the detector and is followed by L.F. stages, the grid leak should be connected, as shown in Fig. 14, between the grid and the low-tension + lead of a battery-driven set, and may have a value of about ½ megohm, used in conjunction with a grid condenser with a capacity of 0·0002 mfd.

More complicated circuits may have the grid resistance connected either to negative or positive low tension, or to a potential divider or a potentiometer, according to the desired biasing of the detector grid.

Anode Resistances

These are used in the anode circuit of a valve, generally wire wound, non-inductive and enclosed in a carton or casing of some kind with terminal or tag connections at each end.

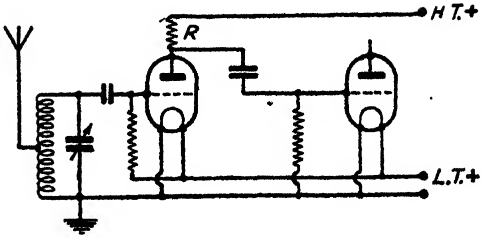


FIG. 15.—ANODE RESISTANCE.

Skeleton circuit of a resistance-capacity coupling.

An example of the use of such resistances is the simple resistance-capacity coupling between a detector valve and a L.F. valve, of which a skeleton circuit is shown in Fig. 15, with the coupling resistance R, but without the usual choke and decoupling arrangements.

As a general guide, the value of the coupling resistance should be about three to four times that of the impedance of the valve, thus with a valve having an impedance of 18,500 ohms, the anode resistance may be of the order of 70,000 to 80,000 ohms.

Tapped Anode Resistances

When relatively heavy currents have to be handled, as in the case of power amplifiers, it is essential to use a special type of heavy duty resistance, consisting of a wire-bound resistance on poreclain formers supported on uprights. It should be placed in the set so that there is ample space around the resistance to allow for heat radiation. By winding the resistance in two halves, it can be centre tapped and the two parts used respectively as anode and decoupling resistances.

Values range from 2,000 ohms, 100 milliamps., to 20,000 ohms, 30 milliamps. Adjustable clips enable the resistances to be tapped at any convenient points.

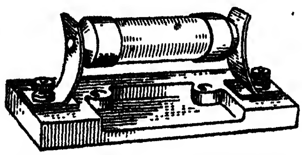


FIG. 16.—EARLY TYPE OF CARTRIDGE RESISTANCE AND HOLDER.

Anode Feed Resistances

The cartridge type resistance, Fig. 16, has a dissipation of 2½ watts, is wound in sections and enclosed in a cartridge with metal contact ends which spring into a especial holder, the standard range

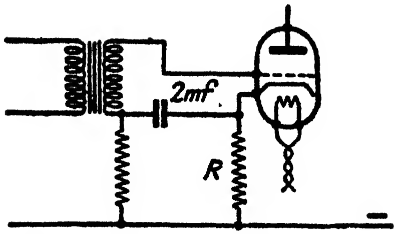


FIG. 17.—GRID BIAS RESISTANCE IN A CIRCUIT.

Showing how the resistance R is incorporated in an all-mains set.

is 300 to 100,000 ohms. The power type dissipates 10 watts and ranges from 500 to 8,000 ohms.

Other types are made with the resistance in a neat moulded casing, in appearance like a fixed condenser, while others combining a resistance or resistances and a fixed condenser are on the market and result in a great economy of space and simplification of layout.

Grid Bias Resistances

These resistances are non-inductively wound with impregnated D.S.C. Eureka resistance wire on sectional bobbins and enclosed in a moulded Bakelite casing with terminals on the base, or are fitted with end-caps and wires for soldering in position. Values are normally up to 1,500 ohms.

The application of such a resistance in a skeleton circuit for an all-mains set is shown in Fig. 17.

Variable Resistances

There are numerous types, which can roughly be grouped into three sections: first, the plain straight-slider type, now nearly obsolete; secondly, the circular type; and, lastly, the tapped variety with selector switch.

Claims for the tapped variety are that the studs and tappings eliminate wear on the resistance element which can then be wound with covered wire.

In one make, 14 contact studs are used with equal resistance values between each, giving a smooth control suitable for variable dropping resistances, while a similar variety, but wound logarithmically, is suited to volume controls. Average dissipation is about 3 watts, resistance 50,000 ohms.

One application of a variable resistance is shown in Fig. 18, where it is shunted across a condenser in series with a loudspeaker. The purpose here is to control the tone of the speaker; when the resistance is in circuit, the bass is diminished according to the value of resistance and electrical characteristics of the circuit and the speaker.

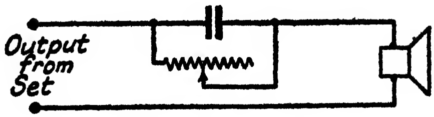


FIG. 18.—VARIABLE RESISTANCE AS TONE CONTROLLER.

The amount of bass response can be regulated with the variable resistance.

An average value for the resistance is about 10,000 ohms with a $\frac{1}{4}$ mfd. to 1 mfd. condenser.

The treble can be controlled by putting the condenser in series with the resistance and shunting both components across the loudspeaker.

Wire-wound Spaghetti Resistances

Under this general heading will be found a variety of makes, differing somewhat in detail. One type has a braided silk covering over the resistance wire, and open tag ends. In another type, the wire element is electrically spot-welded to coiled copper connection to the tag ends.

The resistances are often wound on a special core, have double grip terminal tags, and are very flexible. They can be knotted when necessary to reduce their mechanical length, without loss of electrical efficiency.

Biasing Spaghettis for Heavy Duty Purposes

These are intended for biasing mains valves or other heavy duty purposes, the current carrying capacity is higher than the usual spaghetti types.

Applications of these resistances are too numerous to particularize, they can be used in almost any home constructor set, and are simply clamped in place by the terminal nuts on the components they connect.

Wire-wound Resistances

These are wound on an insulating core and have terminals and clip connections at each end. Wire-wound resistances are normally designed for loads up to 10 watts. Larger sizes, capable of dissipating about twenty watts, can be obtained.

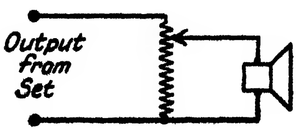


FIG. 19.—POTENTIOMETER IN LOUDSPEAKER CIRCUIT.

Here the resistance is shunted across the output leads and the movable contact connected to one of the loudspeaker leads.

Direct Current Mains Resistances

Employed to reduce the voltage from the mains, they must in all cases be well spaced from any other fittings or from the sides of the cabinet, as they have to dissipate some 50 watts or so in the form of heat depending on the current required.

Such resistances are usually wound with nickel-chrome wire on porcelain or heat-resisting tubes, having tapping bands or clamp rings and terminals.

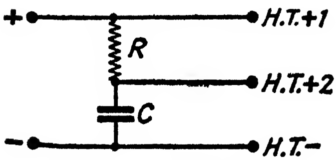


FIG. 20.—ANODE FEED SYSTEM.

A voltage drop is obtained between H.T. + 1 and H.T. + 2 by the resistance R.

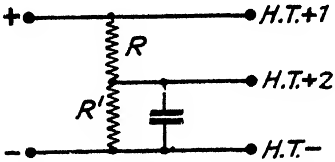


FIG. 21.—SCREEN GRID FEED RESISTANCES.

The two fixed resistances used to control the voltage to the screen of a S.G. valve.

Voltage Dropping

Provision of various output voltages from an eliminator or power unit can be obtained by various methods, including the anode feed system shown in Fig. 20, which by use of a suitable resistance R and a condenser C reduces the voltage of the H.T. tap and acts as a decoupler, the condenser by-passing unwanted frequencies to earth.

The value of resistance R can be calculated if the load or maximum voltage is known, and the required anode voltage and current. Deduct the lower voltage from the maximum, divide this by the current flowing through the resistance in milliamperes, and multiply by 1,000 to obtain the value in ohms for the resistance. For example, with a maximum voltage of 150 and detector anode voltage of 90, the voltage to be dropped is 60. Assume the current is 3 milliamps, then

$$\frac{60}{3} \times 1{,}000 = 20{,}000 \text{ ohms.}$$

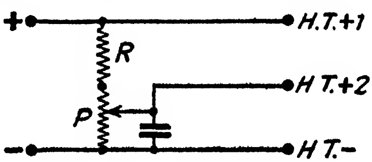


FIG. 22.—RESISTANCES AND POTENTIOMETER CONTROL.

Substituting a potentiometer P for the resistance R[1] of Fig. 21 enables the screen voltage to be varied for maximum results.

When two or more resistances are used in series to provide various voltage outputs—as, for instance, the supply to a screen grid valve or anode bend detector—the current flow is, in such cases, quite small, and to avoid undesirable fluctuations the value of the potentiometer or potential divider must be such that about four times the current taken by the valve will flow through it. The skeleton circuit is shown in Fig. 21, with resistances at R and R^1.

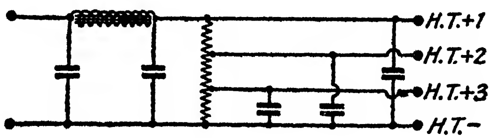


FIG. 23.—POTENTIAL DIVIDER.

A fixed resistance with tappings at equal divisions here provides three different voltage outputs.

If it is desired to supply a variable voltage to the screen, a potentiometer can be substituted for the fixed resistance R^1 and should have the value calculated above or something very near it; the skeleton circuit is shown in Fig. 22 and will be found adaptable to many practical circuits. A development of the same idea, with three separate voltage outputs, is shown in Fig. 23, with a potential divider across the main leads and equal tapping points giving voltages of, say, 180 maximum, 135 at first tap, 90 at the second tap.

Decoupling Resistances

These are introduced into circuits to offer a very high resistance to high-frequency currents, and are employed in conjunction with a fixed condenser which offers relatively low resistance to such currents.

Consequently, the unwanted or used signal currents in, say, the anode circuit of a valve are prevented from flowing into the H.T. circuit as they have an easier path open to them through the condenser to earth, as in Fig. 24, where R is a coupling resistance and R^1 the decoupling resistance.

Pre-set Resistances

The pre-set resistance has many practical uses. It enables the exact value of resistance to be adjusted to a nicety. It consists of a special wire winding on a porcelain former which

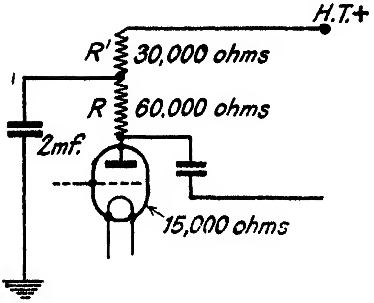


FIG. 24.—DECOUPLING RESISTANCE.

A resistance is here shown at R', which opposes the H.F. currents and by-passes them through the 2 mfd. condenser to earth.

can be mounted anywhere on the panel or baseboard, or on a metal chassis.

An adjustable finger contact regulates the amount of resistance in the circuit.

Metallized Resistances

These are of the non-wire-wound type and serve the purpose of voltage dropping resistances, for providing tappings of various voltages in H.T. apparatus, for decoupling resistances in amplifiers, and for providing grid bias voltages, etc.

Sparking Plug Resistances

These are designed to reduce the interference arising from the sparking plugs and ignition system of cars. They are provided with a socket at one end to screw on to the terminal thread of the sparking plug.

Interchangeable Wire-wound Cartridge Type Resistance

These resistances, as the name implies, are constructed in cartridge form with end connections, which are located in spring clips mounted on an insulated holder. The normal range is from 300 to 100,000 ohms.

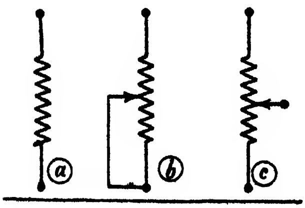


FIG. 25.—SYMBOLS USED FOR DENOTING RESISTANCES AND POTENTIOMETERS.

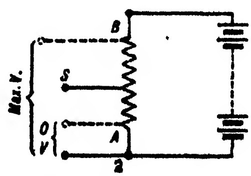


FIG. 26.—HOW A POTENTIOMETER IS GENERALLY CONNECTED.

POTENTIOMETERS

The underlying principles of resistances and potentiometers are almost identical. A potentiometer is merely a resistance from which a tapping is taken: the tapping can be either a fixed or variable one.

A potentiometer is, in appearance, almost identical with a variable resistance. It has, however, three terminals instead of two. Of these, one is in contact with the slider, and the other two are joined to the ends of the resistance element. The latter also is the same as that of a variable resistance, consisting either of a graphite composition or wire.

The object of a potentiometer is, as the name implies, to provide a potential rather than a voltage. By a "potential" we generally mean (although somewhat unscientifically, perhaps) an electrical pressure which is accompanied by a very small current. The usual type of variable potentiometer is denoted by the symbol shown at (*c*) in Fig. 25. It is connected in a circuit of the type represented in Fig. 26. When the slider is in position A, the potential between points S and 2 is zero, but as the slider is moved towards position B, the potential gradually reaches the maximum of the supply from the battery.

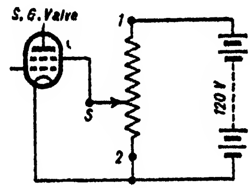


FIG. 27.—USE OF POTENTIOMETER TO PROVIDE SCREENING GRID POTENTIAL TO S.G. VALVES.

The principal use of potentiometers in wireless circuits is to provide the screening grid potential to S.G. valves, and to act as volume controls in various ways.

When employed for the former purpose, the potential is proportional to the position of the slider. This can be explained more fully by making reference to Fig. 27. When the slider is at that end of the resistance element marked 1, the screening grid potential is equal to that of the high-tension battery, namely 120 volts, but when moved to the end marked 2, the potential is 0. When set midway between ends 1 and 2, the S.G. potential is 60 volts. In the same way it will be seen that when the slider is three-quarters of the way up from 2, the S.G. potential is 90 volts.

Graded Potentiometers

As explained, the potential derived from the usual type of potentiometer is proportional to the position of the slider. Thus the resistance between the slider and one end of the resistance element is varied by the same amount when the control knob is turned from 0 to 10 degrees, as when it is turned from, say, 150 to 160 degrees. This is convenient when the potentiometer is used for most purposes, but there are some cases for which it is far from ideal. For instance, when the usual type of potentiometer is used for controlling the volume from a pick-up, it has little effect over the first quarter revolution or so, whilst when the slider approaches the end of its travel, a very slight movement causes a tremendous change in volume.

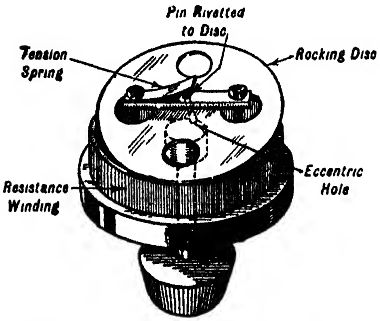


FIG. 28.—PRINCIPLE OF ROCKING PLATE POTENTIOMETER.

To overcome this drawback, a number of " graded " potentiometers are available. These are so constructed that the change of resistance for any given amount of slider movement decreases as the slider is moved from " maximum " to " minimum " volume, or from 0 to the highest scale reading. In most instruments this is provided by winding the resistance wire on a tapering strip of insulating material, and so making the turns of diminishing lengths.

The methods of making contact between the resistance element and the slider are generally the same as those employed in the case of resistance.

Realising, however, that the rubbing action of the usual slider is bound to wear away the very fine resistance wire sooner or later, one or two better systems have been devised.

The most notable of these is that in which a rocking disc is used. By mounting the disc at an angle to the spindle it is " rocked " round the resistance element; it does not rub at all, and consequently the wear on the wire is nil. A sketch of the idea is given in Fig. 18.

Ganging

To make it possible to control two or more potentiometers by a single knob, some types of potentiometer are made in such a way that any number can be ganged together. One method employed is to allow the threaded spindle to project from the bottom; by using a threaded " union " this can be attached to the spindle of another component.

Ganged potentiometers are very useful for controlling the volume of both radio and gramophone reproduction. By using one potentiometer to control the grid bias of a variable-mu S.G. valve and the other to act on the pick-up, one knob can be used for both purposes. This simplifies the panel lay-out and makes for greater simplicity of operation. The above is just one example of the use of ganged potentiometers, and there are many others which will occur to the reader.

Before leaving the subject of variable potentiometers, mention must be made of a special kind which is popular. This is the potentiometer with which is combined a toggle switch. The switch can be used for connecting the set to the power supply, and the potentiometer, for a volume control. By moving the control knob just past the position of minimum volume, a lever on the end of the spindle turns off the switch. Combined potentiometer-switches of this kind are also very useful for providing a variable grid bias for variable-mu valves of the battery-fed type; the switch can be used to break the circuit between the potentiometer and G.B. battery, thus avoiding waste of G.B. current (through the potentiometer windings), whilst the set is out of use.

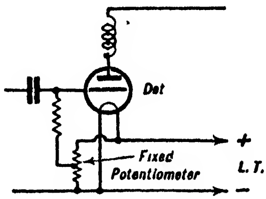


FIG. 29.—SHOWING USE OF FIXED POTENTIOMETER FOR CONNECTING GRID LEAK TO A POINT OF POTENTIAL SOMEWHERE BETWEEN THE EXTREMES OF L.T. POSITIVE AND NEGATIVE.

Fixed Potentiometers

In many types of battery receivers better results are to be obtained by connecting the grid leak to a point of potential somewhere between the extremes of L.T. positive and negative. The exact point is not very critical, and so a fixed or pre-set potentiometer can be used for the purpose. The latter generally

takes the form of a small non-inductively wound resistance from which a tapping is taken; its connections are as shown in Fig. 29.

Another use for a fixed potentiometer or centre-tapped resistance is to provide an artificial centre-tap for untapped L.T. windings of mains transformers.

HOW TO CHOOSE RESISTANCES AND POTENTIOMETERS FOR WIRELESS CIRCUITS

We will now consider the circuit diagram in Fig. 30 and decide on the correct components to employ in the positions marked from R1 to R16.

The circuit does not necessarily represent an ideal, or even a good arrangement. It does, however, incorporate most of those features to be found in a S.G.-D.-Pen. A.C. receiver.

Pre-detector Volume Control

The volume control resistance R1 is used in connection with the condenser C1 to damp the tuning of the aerial coil. Its principal use is to reduce the input from the local station and so prevent overloading of the first valve. Being in shunt with a tuned circuit, it must clearly be non-inductive (not wire wound) and should have a maximum value in the region of 50,000 ohms.

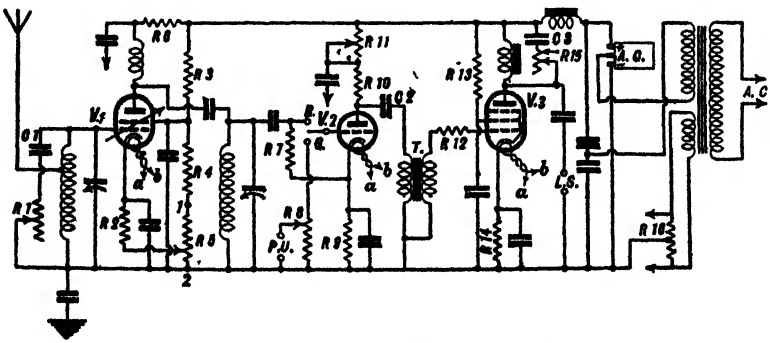


FIG. 30.—TYPICAL CIRCUIT DIAGRAM.

The method of arriving at the correct values for the various resistances and potentiometers shown is discussed in the text.

Variable Automatic Grid Bias

R2 and R5 act together to provide a variable grid bias to the variable-mu S.G. valve. R2 serves to decouple the cathode and also to provide a minimum degree of bias when the slider of potentiometer R5 is turned to the end marked " 2." Suppose the total H.T. current consumption of V1 is 5 milliamperes (4 milliamperes to the anode and 1 milliampere to the screening grid) and that the minimum amount of bias required is $1\frac{1}{2}$ volts ; R2 will therefore require to have a resistance of $1{\cdot}5/1 \times 1{,}000/5$ (from $R = E/I$), or 300 ohms. The resistance should for preference be non-inductive, but this is not essential, since even a wire wound resistance of 300 ohms would have an inappreciable inductance. R5 should have such a resistance that V1 is biased to maximum extent when the slider is at the end marked " 1." If the maximum bias is, say, 12 volts, R5 will have to provide 10·5 (12 — 1·5) volts, so its resistance must be $\frac{10{\cdot}5}{1} \times \frac{1{,}000}{5}$, or 2,100 ohms. In practice, we should probably choose a 2,000-ohm component for convenience.

Screening Grid Supply

The fixed resistances R3 and R4 together form a fixed potentiometer which supplies H.T. to the screening grid of V1. When a potential of 80 volts is required and the voltage of the supply is 250, the ratio of R4 plus R5 to R3 must be as 80 is to 170 (250 — 80). A suitable total resistance for R3 plus R4 plus R5 is 100,000 ohms, and therefore, by simple proportion, R3 should be of 68,000 ohms and R4, 30,000 ohms (32,000—2,000 for R5). After making the calculation as above we should choose standard resistances which were nearest in value to the calculated figures.

Grid Leak

We have considered R6 before, on page 156, so we can pass on to the detector grid leak R7. The value of this is dependent upon the type of rectification desired. When normal leaky grid rectification is employed a resistance in the region of 2 megohms (2 million ohms) is correct, but for power grid detection the value must be reduced to $\frac{1}{2}$ or even $\frac{1}{4}$ megohm. A grid leak must always be absolutely non-inductive.

Detector Grid Bias

When the set is to be used for gramophone reproduction, the valve V2, which normally functions as detector, acts as a low-frequency amplifier, and therefore requires a certain amount of negative grid bias. The latter is provided by the fixed resistance R9, which may be either wire-wound or non-inductive.

The value of R9 will be found in exactly the same way as that of R2. Thus, if a bias voltage of 1 is required, and at this figure the valve passes 2 milliamperes, the resistance should be 1 × 1,000/2, or 500 ohms

Pick-up Volume Control

The actual resistance of the pick-up volume control potentiometer R8 is dependent principally upon the pick-up employed. For instance, with a high impedance unit, the resistance should be not less than 250,000 ohms, whilst when a lower impedance pick-up is used, 50,000 ohms is a more suitable value. In nearly all cases the makers specify the correct value of resistance required.

As mentioned earlier, a "graded" potentiometer will give the "smoothest" control of volume, and is to be preferred for position R8.

Parallel Feed

The fixed resistance R10 is used in conjunction with the coupling condenser C2 and L.F. transformer T to provide resistance fed, or parallel fed transformer coupling. The optimum resistance of R10 is from twice to two-and-a-half times the impedance of the detector valve V2. Thus if a valve having an impedance of 18,000 ohms were used for V2, R10 should be of about 40,000 ohms. A non-inductive or low-inductance resistance is best for this position.

De-coupling

R11 is a variable resistance used to de-couple the anode circuit of V2, and to provide a variable anode voltage. Its value can be calculated in the same way as that of R6. Any type of variable resistance, either wire-wound or otherwise, will be suitable. R13 serves to de-couple the priming grid of the pentode. Any value from 5,000 to 10,000 ohms is suitable, and the resistance may be either inductive or non-inductive.

" Stopper " Resistance

The fixed resistance R12 is a " stopper " to prevent the passage of high-frequency currents into the pentode amplifier circuit. Any non-inductive resistance of from 10,000 to 100,000 ohms will serve here. It must offer a high impedance in proportion to that of the small condenser formed by the grid and cathode of V3. The best value *can* be found by calculation, but in practice it is more usual to find it by experiment. When the correct value has been chosen, it should be possible to touch the anode terminal of V3 without causing a whistle to be emitted by the speaker or a reduction in signal strength.

Pentode Bias Resistance

The automatic bias resistance R14 acts in the same way as resistances R2 and R9, and its value is calculated in the same way.

Assuming V3 to take 35 milliamps H.T., and to require 11 volts grid bias, R14 should be of approximately 300 ohms.

All those resistances previously considered carry only small amounts of current, so it has scarcely been necessary to consider their power ratings. But as R14 has to deal with a comparatively large amount of current, we had better see what its power rating should be. Using our formula $W = I \times E$, we get $W = 35/1{,}000 \times \frac{11}{1}$, which cancels out to rather less than half a watt. Nearly any type of small resistance will therefore be suitable.

Tone Correction

Since a pentode valve generally tends to give emphasis to the higher musical frequencies, it is usual to employ a tone correction device with it. This latter generally consists of a variable resistance and fixed condenser connected in series across the primary of the output transformer, or across the output choke, as shown at R15 and C3 in Fig. 30.

The object is to provide a fairly easy leakage path for higher frequencies, whilst at the same time arranging that the " leakage " shall be as small as possible for lower frequencies. This can be provided for by so proportioning the values of C3 and R15 that they resonate to a low frequency.

When C3 is 0·01 mfd., R15 should have a maximum resistance

of 50,000 ohms. By adjusting the variable resistance, a varying degree of high note attenuation can be obtained.

Practically any type of 50,000 ohm resistance will be correct for R15.

Artificial Centre Tap

The object of R16, which is a centre-tapped resistance, is to provide an artificial centre tapping for the 4-volt winding of the mains transformer.

CHAPTER VII

CHOKES

RADIO-FREQUENCY CHOKES

THE best known use of a high-frequency choke (in future we will refer to it by the popular abbreviation of "H.F.C.") is in the anode circuit of a detector valve with which reaction is obtained by means of a fixed reaction coil and a variable condenser. For convenience a skeleton circuit of the arrangement is given in Fig. 1.

In the first place, the choke should offer uniform resistance (or more correctly, impedance) to the frequencies represented by all the wavelengths to which the receiver can be tuned. The latter generally extends from about 200 to 2,000 metres. To obtain this result entails that the natural wavelength of the choke should be well in excess of 2,000 metres and, as a matter of fact, the best results are generally obtained by designing the choke so that it resonates (tunes) at a wavelength in the region of 4,000 metres. This makes it necessary to use a very large number of turns of wire and explains why the better-class chokes are somewhat expensive.

The same explanation shows why many receivers are inefficient on the long waveband though quite satisfactory on medium waves. The choke employed has too low an inductance to be effective on long waves although its inductance is sufficient to provide the necessary "stopping" effect on lower wavelengths. Incidentally, it might be added here that the fault just mentioned can usually be distinguished from the fact that above a certain wavelength the reaction control has to be advanced

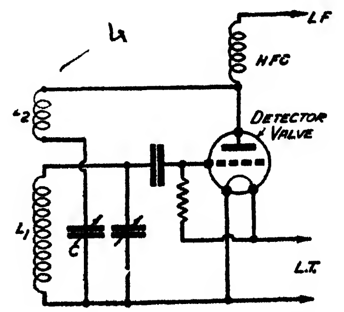


FIG. 1.—USE OF H.F. CHOKE IN ANODE CIRCUIT OF DETECTOR VALVE WITH REACTION.

well beyond its normal setting. It also sometimes happens that a low-priced choke actually resonates to a wavelength on the long waveband. As a result, reaction is unsatisfactory above and below a certain wavelength. Just *at* that wavelength, however, it is particularly strong and generally " fierce," or difficult to control.

Capacity and Resistance

In addition to possessing a high inductance value a good choke should also have a very low self-capacity because, if high, the capacity would permit of leakage of high-frequency currents across it. The capacity might also in some cases make the choke tune sharply to a particular wavelength instead of having the required even response to a wide band of wavelengths. With the object of cutting down capacity, the windings are usually divided into a number of sections as shown in the sketch of Fig. 6.

A good choke should also, for many purposes, have a low resistance to D.C. currents. This means that it must be wound with comparatively heavy gauge wire, which again means increased cost.

Other Uses of H.F. Chokes

So far we have considered H.F. chokes only in relation to their function as " stoppers " in the anode circuits of regenerative detector valves, but they have a considerably wider field of utility than this, as can be judged by examining the circuits of Figs. 2, 3, 4 and 5.

Let us first look over the arrangement depicted by Fig. 2. This is a skeleton circuit of an S.G.-D.-P. A.C. receiver—the power supply circuit has been omitted for simplicity.

The choke marked " *c* " is the one we have already considered. Choke " *b* " acts in a rather similar manner and its function is to prevent the signal currents in the anode circuit of the S.G. valve from following the path indicated by the dotted arrow into the high tension supply circuit. By doing so, the currents are compelled to pass into the tuning circuit of the detector valve by the path marked with full-line arrows.

A choke for this position must be as near as possible to the ideals we have previously established. Its impedance at all

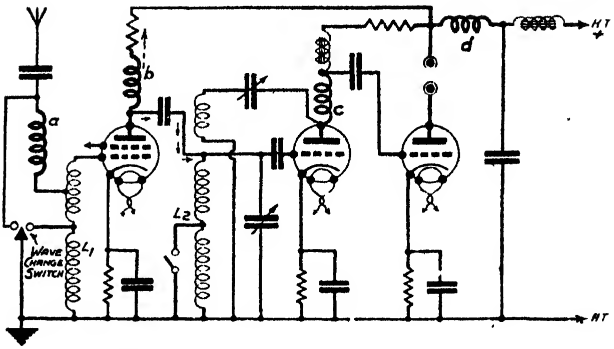


FIG. 2.–SKELETON CIRCUIT OF S.G.-D.-P. A.C. RECEIVER.

Showing where H.F. chokes are required (shown as heavy lines).

wavelengths must be high in relation to that of the screened-grid valve. This means that it must have an inductance (which is in effect a measure of the impedance) of no less than 200,000 micro-henries. At the same time, the self-capacity should not exceed some 4 micro-microfarads.

As the choke is virtually in parallel with the tuned grid coil L.2, it would damp the tuning of the latter if its impedance were too low. In addition, the amplification afforded by the S.G. valve would be reduced if the impedance of the choke were not in excess of that of the valve.

Medium Wave Stopper

The choke marked "*a*" is a medium wave "stopper" and it must have a natural wavelength lower than the lowest wavelength covered by the long wave coil (generally about 1,000 metres), and higher than the highest wavelength of the medium wave coil (550 metres approximately), so that it will offer an equal impedance to all signals on the medium waveband. The choke, of course, must be short-circuited by the wave-change switch for medium wave reception, as shown in Fig. 2.

Choke "*d*" is not often employed but is very useful in some cases of instability and unsteady reaction control. It prevents any "stray" H.F. currents from passing into the power supply. A choke for this position does not require to have a particularly high inductance but must be capable of carrying the total anode current of all three valves. Similar chokes can also often be used to advantage in the mains supply leads, particularly in the leads to a D.C. eliminator employed for H.T. supply only.

Mains Lead Chokes

Other chokes of the same type, but capable of carrying currents up to 0·6 ampere, are also available for connecting in the mains leads to an all-A.C. or an all-D.C. receiver. It is not generally necessary to connect chokes in the mains supply leads, but they are exceedingly useful in cases where high-frequency apparatus is operated from the mains, for this often superimposes a H.F. "ripple" on the mains supply. This is usually indicated by a "bubbling" or "rippling" sound in the speaker. Before trying the chokes, however, disconnect the aerial to make sure that interference is not being picked up from some outside source.

Short-Wave Chokes

A different kind of choke is required in a short-wave receiver of the type shown in the circuit of Fig. 3. The choke marked "S.W.H.F.C." acts in the same way as that indicated at "*c*" in Fig. 2, but has to deal with much higher frequencies and therefore requires to have a correspondingly lower inductance. Its self-capacity must also be as low as ever possible because unwanted capacity is much more detrimental in a short-wave receiver.

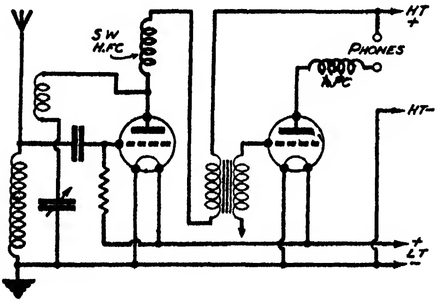


Fig. 3.—Two Uses for Chokes in a 2-valve Short-Wave Receiver.

Short-wave chokes are generally made similar to that shown in Fig. 8. To keep down capacity, the winding is put in a single layer on a thin ebonite tube and the turns are spaced.

Another use for a H.F.C. is illustrated by Fig. 3. When using phones with a short-wave receiver it often happens that hand-capacity effects are very troublesome and that "howls" and "squeaks" are heard when the phones are touched. This is due to stray H.F. currents leaking into the phone leads, so the obvious remedy is to keep them in check by inserting a choke between the last valve and the phones. The choke should really be of the short-wave type, but very often one of the normal pattern will serve sufficiently well.

Fig. 4 shows the circuit of the first detector and intermediate-frequency amplifier of a short-wave superheterodyne. In this case, a short-wave choke is used for the normal purpose of keeping H.F. currents out of the amplifier and a second (long wave) choke is used in conjunction with a tuned grid coil to couple the two valves together. This second choke has to deal with the "beat frequency" which generally corresponds to a wave-length of 600 metres or so, and therefore any normal component will serve the purpose.

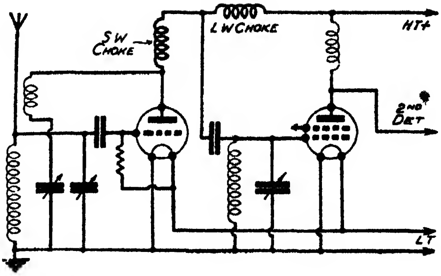


Fig. 4.—H.F. Chokes in a Short-Wave Superheterodyne.

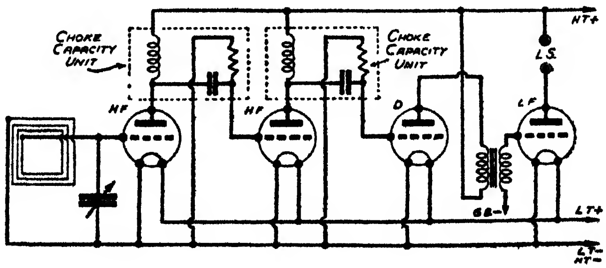
Choke-Capacity Coupling

In some receivers, in which a high degree of efficiency is not called for, or where ease of tuning and low weight are primary considerations (in a portable, for instance), choke-capacity coupling is employed between the H.F. stages and between the H.F. and detector valves. A circuit of such an arrangement is shown in Fig. 5, from which it will be seen that the choke functions in exactly the same manner as "*b*" in Fig. 2.

The Second Detector

Special chokes are available for use in the anode circuit of the second detector valve of a superheterodyne. The latter valve has to deal only with a single frequency, that of the intermediate-frequency amplifier, and so the design of a suitable choke is an easy matter. The frequency is generally about 110 kilocycles,

Fig. 5.—Circuit of a Choke-Capacity Coupled H.F. Amplifier.



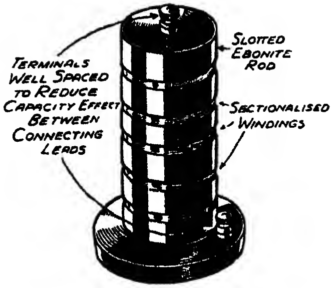
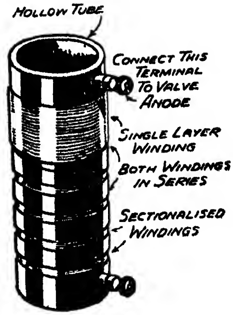


Fig. 6.—Commonest Form of H.F. Choke Construction.



Fig, 7.—Construction of a Choke Required for both Long and Short Wavelengths.

which corresponds to a wavelength of approximately 2,700 metres, and in consequence a suitable choke must have a higher inductance than the normal type, but a little extra self-capacity does not matter.

Forms of Construction

And now, having considered the principal uses of H.F. chokes, it will be interesting to see how they are made. The sketch of Fig. 6 shows the most common form of construction; the winding is divided into a number of sections so as to keep down self-capacity. A solid rod of ebonite with turned slots generally serves as former, but some makers replace the rod by a tube with a view to still further reducing capacity losses.

Another well-known and popular type of choke is that shown in the sketch of Fig. 9. In this case, the windings are put on a single bobbin of fairly large diameter. The self-capacity is somewhat higher than with other types of choke, but the component is quite good enough for use in the anode circuit of a detector valve which is not required to operate on wavelengths above about 1,800 metres or below 200 metres.

With a view to making the choke more suitable for covering both long and short wavelengths, some manufacturers have adopted the excellent form of construction shown in Fig. 7. Here the winding is divided into two parts; the short wave portion is wound as a single layer to reduce self-capacity but the long wave winding is pile-wound in the usual manner in a number of slots.

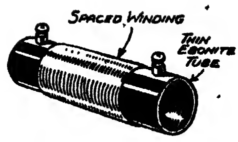


FIG. 8.—GENERAL FORM OF CONSTRUCTION FOR A SHORT-WAVE CHOKE.

Another choke designed on a similar principle is wound on a tapered former. In this case all the windings are put in slots but as the ebonite former tapers towards one end the slots are of decreasing diameter, and in consequence contain decreasing lengths of wire; the smaller diameter windings have a smaller self-capacity. In all chokes of this type, the "low capacity" end of the winding should be joined to the anode of the valve. By connecting in this way, any capacity at the other end of the choke is of no consequence when dealing with short waves because the H.F. currents do not "penetrate" so far.

Preventing Inter-Action.—Chokes, like tuning coils, have a magnetic field, and can therefore cause inter-action if placed near, and parallel to, other chokes or coils. Two methods of avoiding this difficulty are in common use. One is to divide the choke into two parts as shown in Fig. 10. As the windings on the two small chokes go in opposite directions the two magnetic fields tend to cancel each other.

Another way of preventing inter-action between chokes and other components is to build the chokes into screening cans. As the screening lowers the effective inductance, the windings must be designed to have an actual inductance in excess of the figure eventually required.

THE MAGNETIC PROPERTIES OF IRON

As low-frequency and smoothing chokes are wound on laminated iron cores, some knowledge of the magnetic properties of iron is desirable before considering these components, and the subject is dealt with briefly in the following paragraphs.

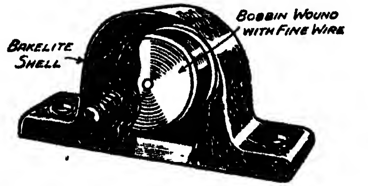


FIG. 9.—EARLY TYPE OF CHOKE SUITABLE FOR ANODE CIRCUIT OF A DETECTOR VALVE OF WAVELENGTHS BETWEEN 200 AND ABOUT 1,800 METRES.

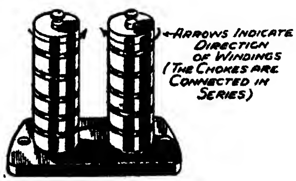


FIG. 10.—CONSTRUCTION OF A BINOCULAR CHOKE.

It is well known that if a coil of wire be wound round a piece of iron rod and a current be passed through the coil that the iron will become magnetized. Obviously the energy which produces this effect is from the current in the coil of wire and is called the MAGNETIZING FORCE.

It will be found by experiment that the magnetism will vary according to the number of turns round the iron and the current through the turns, and that there is a relationship between the turns, the current through them and the magnetizing force. To this magnetizing force the symbol H has been given, and various units are used to express the amount of this force, the most common of which is AMPERE TURNS. These are taken per unit length of a coil or solenoid, and H is taken as being equal to $\frac{4 \times \pi}{10}$ times the number of amperes flowing in the coil, times the number of turns per centimetre length of the coil.

Magnetic Force

Now our coil of wire round the piece of iron will, when current flows through it, exert a magnetizing force upon the iron, and lines of magnetic force or flux, as they are commonly called, will start at one end of the iron, travel through space to the other end and return back to the point of start. The end at which the lines of force emerge is generally known as the North Pole of the magnet, the other end is known as the South Pole, and the path of the lines is obviously the route taken by them producing a field or area acted on by the lines round the magnet, in three dimensions.

Flux Density

This flux will naturally be more dense the greater the amount of magnetism in the iron, and it is customary to represent the flux density by the symbol B. This flux density B is equal to the numerical value of the lines of magnetic force or flux per square centimetre.

Permeability

If we check the number of lines of force issuing from our piece of iron and then remove it carefully from the core of the coil, we shall find that there are still lines of force issuing from

the coil, but not so many as was the case when the iron was in the core of the coil. Obviously the iron is a very much better " conductor " of lines of magnetic force than the air which now occupies the core of the coil. This property of conducting lines of magnetic force is known as PERMEABILITY, and to it is given the symbol μ (pronounced " mew "). The conducting property or permeability of air is taken as a standard and considered to be equal to 1.

It has been found that there is a definite relationship between these three properties. Magnetizing Force (H), Flux Density (B), and Permeability (μ).

B is equal to μ multiplied by H ($B = \mu H$), and μ is equal to B divided by H $\left(\mu = \frac{B}{H}\right)$.

Now we have been considering, purely as an illustration, a coil of wire wound round a piece of iron with a current flowing through the coil.

It will be obvious that since the iron was in the form of a rod the lines of force passing from one end to the other would have to travel through air and therefore accurate measurements of its magnetic properties could hardly be taken in this manner.

A closed iron circuit is usually employed in taking such measurements and may take the form of a ring, a square or a rectangle. It is customary to demagnetize the material under test prior to the test. This is usually done by passing an alternating current through a coil round it and slowly reducing the value of the current to zero.

An instrument known as a Flux Meter is used to measure the flux density. A well-known type is the Grassot Flux Meter, which is really a form of galvanometer having a very lightly damped pointer which has been calibrated in flux lines under certain conditions. The pointer is so free to move that it takes many seconds, sometimes minutes, to return to its zero if displaced.

Residual Magnetism and Hysteresis

Now, assuming that we have a closed iron circuit of the type described above, together with suitable means for magnetizing the iron and for observing the effect produced by such magnetization, we can plot a graph showing the relationship between

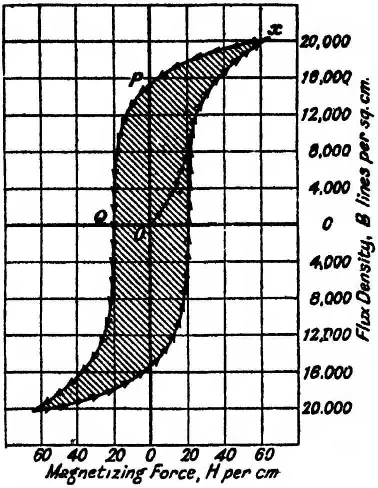


FIG. 11.—A HYSTERESIS LOOP.
This is a graph showing the relationship between the magnetizing force and the flux density.

the magnetizing force and the flux density, and if we carry the metal through a complete cycle of magnetization and plot our graph we will have a figure described similar to a sort of S (Fig. 11). This figure is caused by residual magnetism and is usually called a Hysteresis Loop.

Hysteresis Loop

In Fig. 12 we have a group or family of such loops taken for several cycles of magnetization. If we consider the curve in Fig. 11, we can by tracing out the curve observe how the magnetism B commences "lagging" behind after the magnetizing force H, for that particular curve has reached its maximum in either a positive or negative direction. The cycle starts at O and the magnetism rises to x, and as the magnetizing force decreases again to O it will be observed that B is now only at P or has lagged behind considerably. The lagging of B behind H is called "Hysteresis." Referring again to our "loop," the area enclosed by the loop will give the loss of energy due to hysteresis, and further where the curve cuts

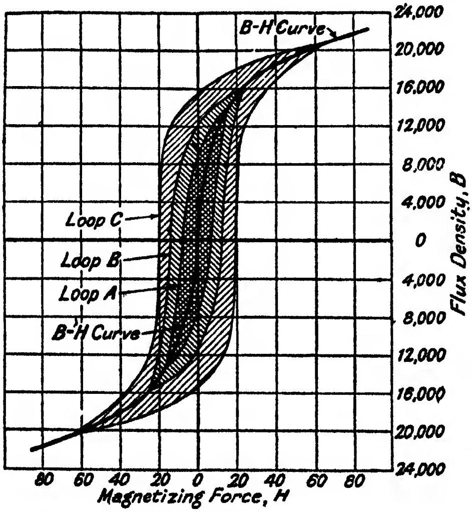


FIG. 12.—A GROUP OR FAMILY OF HYSTERESIS LOOPS. Showing B.H. or "tip-point curve."

the zero line P, the amount OP is the "Remanence," whilst OQ is the coercive force for the given maximum of B represented by that particular curve.

The BH Curve

Referring again to our family of curves, Fig. 12, the line joining the tips of the curves together and passing through the zero is known as the BH curve, and it is from this curve that the values of permeability or μ are taken.

Two things are immediately apparent. One being that the portions of the curves above and below the horizontal line are symmetrical, the other that the smaller the hysteresis loop the less loss will be experienced from this cause. There are, however, certain cases where material having the larger loop may prove more useful, but such instances are few.

In Fig. 13, is shown a hysteresis loop for soft iron wire which used to be employed extensively for the cores of low-frequency inter-valve transformers. Compare this with Fig. 14A, showing a hysteresis loop of Permalloy "C," a high permeability alloy.

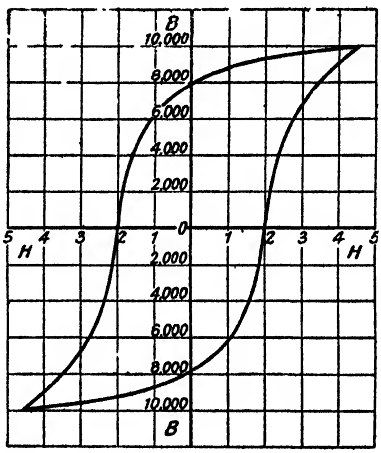


FIG. 13.—HYSTERESIS LOOP OF 22-GAUGE SOFT IRON WIRE.
This material was used extensively for cores of inter-valve transformers.

In Fig. 14B, we have a BH curve for Permalloy "B." A brief inspection of the curves in these three figures will show what considerable improvements have been made in this direction.

Differential or Incremental Permeability

So far we have merely considered the effect of carrying the metal through a complete cycle of magnetization, starting with our magnetizing force at zero, increasing it to maximum in one direction and then reducing it to zero, and repeating the performance in the opposite direction.

If we impress first a certain magnetizing force on the metal and vary it on either side of these limits, as is the case when an inductance such as a choke or primary of a transformer is connected in the anode circuit of a valve, we have first a steady current flowing through the primary—which is the normal anode current of the valve—producing a magnetizing force which we will designate as A in Fig. 15. Superimposed on this we have an alternating current which will one moment increase the magnetizing force to a value C, and the next moment decrease it to E. In fact, the result will be similar to having a maximum magnetizing force of value C, which is periodically decreased to E, and returns again to C—providing our A.C. does not fluctuate in value.

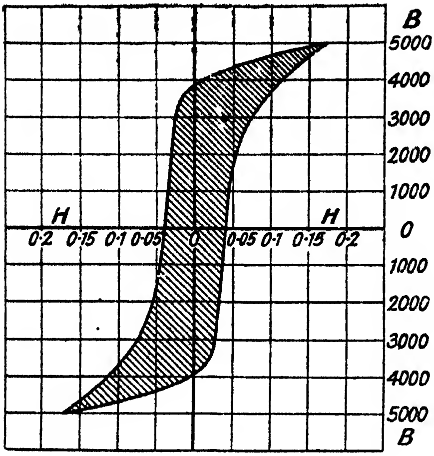


FIG. 14A.—REPRESENTATIVE HYSTERESIS LOOP FOR PERMALLOY "C."

Further reference to Fig. 15 will show a family of hysteresis loops corresponding to the various magnetizing forces E, A, C, etc. The tips of the loops, which are the maximum for that particular magnetization, correspond to flux densities E′, A′, C′. Now the maximum magnetization is at C and the minimum at E.

How, then, shall we arrive at the correct permeability value for our varying magnetization? Obviously we cannot obtain it by the

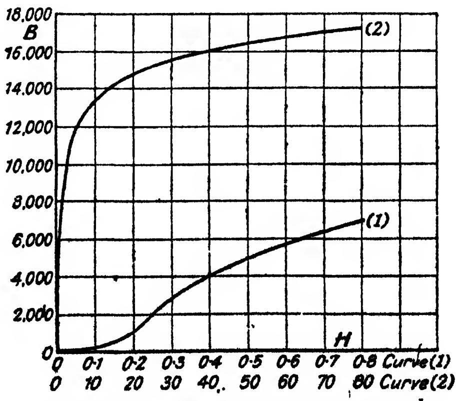


FIG. 14B.—REPRESENTATIVE B.H. CURVE FOR PERMALLOY "B."

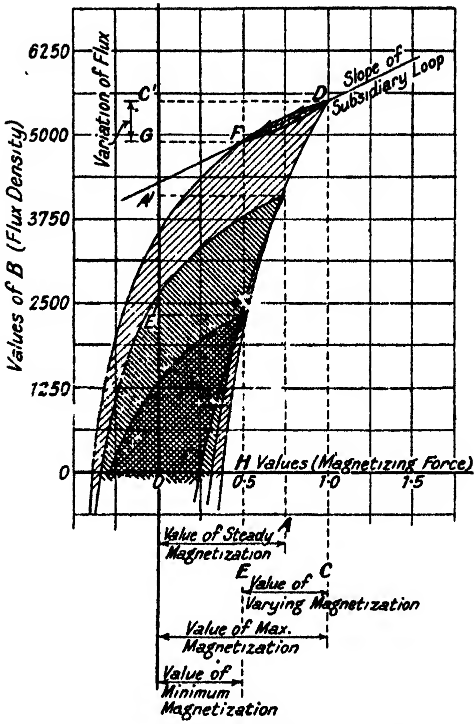


FIG. 15.—SUBSIDIARY HYSTERESIS LOOP.

old process of dividing B by H for either of these values. Let us endeavour to trace the variation of magnetism for a start. Commencing at our maximum magnetization C, corresponding to a flux density C′, we will call the tip of the loop D. As our magnetizing force decreases towards value E, the magnetic flux will follow the curve of the hysteresis loop until we arrive at a point corresponding to E (see Fig. 15). We will call this point on the curve F equal to a flux density G. The magnetization will again increase to C, and the magnetic force will rise from F to D, tracing a small loop as its path. This subsidiary loop is a result of the operation described, and the loss due to hysteresis under these conditions is only the amount equal to the area of this loop—a great deal smaller than would have been the case with the major loop. The line joining F and D gives what is known as the slope of this loop. The steeper this slope the greater will be the value of our differential permeability. It will be noticed that the tip of the subsidiary loop and the tip of the main one coincide as they obviously must do, the magnetization at this point being the same for both.

Use of the Subsidiary Loop.

If we now check the variation of flux density B for the change in magnetization H we will obtain a value OC′ minus OG, which is equal to GC′ and OC minus OE equal to EC. It is usual to

denote the small change in flux density B by the symbols δB or ΔB, and the small change in magnetizing force H by the symbols δH or ΔH. From these values we obtain our value of differential permeability called $\delta\mu$ or $\Delta\mu$ by the simple process of dividing δB by δH, which is of course the same as dividing the value GC′ by the value EC.

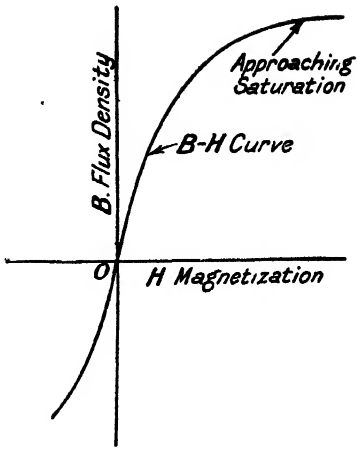


Fig. 16.—Saturation Curve.

This result is called the differential permeability, or, sometimes, the incremental permeability, and, in the case of inductances such as chokes, transformers, etc., used in valve circuits such as described, is the factor taken into account when calculating the inductance value in henries, etc.

Variation of Differential Permeability

It will easily be seen, from the foregoing remarks, that the value of the differential permeability will vary with (1) the polarising current, (2) the superimposed A.C. current; so, therefore, when using such components as chokes and inductances ascertain that the inductance value required has been checked for the required conditions under which it will operate.

With some metals, such as stalloy, the differential permeability is greater with a very little steady magnetization than without. With others any steady magnetization decreases the differential permeability value.

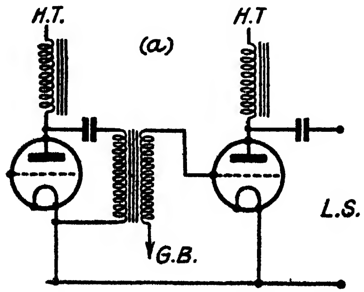


Fig. 17a.—Parallel Choke Feed with Choke Feed Output.

Saturation

Referring again to the paragraph describing the BH curve, and also to Fig. 16, it will be seen that as we increase the magnetizing force and continue to do so, we reach a stage where further increase of magnetization

produces extremely little or no change in the flux density. When this condition has been reached the iron is said to be saturated with magnetism.

The present-day high permeability alloys such as mumetal, radiometal and others approach saturation very easily, and various ways have been employed to obtain the maximum efficiency from them such as employing choke feed coupling and the parallel feed method. The circuits are shown in Fig. 17, A, B and C. This arrangement diverts the steady current from the

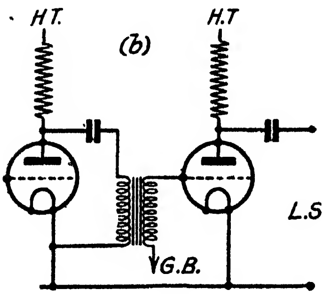


FIG. 17B.—PARALLEL FEED WITH RESISTANCE CAPACITY OUTPUT.

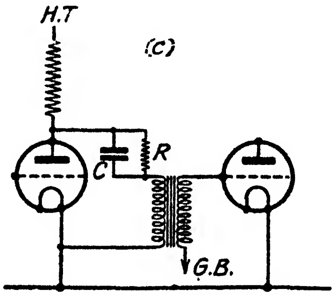


FIG. 17C.—SPECIAL CASE WHERE LEAK R ACROSS CONDENSER C ALLOWS A SMALL POLARISING CURRENT TO PASS.

windings, and the differential permeability value is increased, enabling highly efficient units to be constructed in a small space. Under such conditions the full hysteresis loop is traversed, but with these new metals the area of the loop is so small that the loss of energy due to hysteresis is much less than would at first be imagined.

LOW-FREQUENCY AND SMOOTHING CHOKES

In considering high-frequency chokes we have seen that their principal function was to impede the passage of high-frequency currents. Low-frequency chokes operate in a similar manner in regard to low-frequency currents below, say, 10,000 cycles. A good L.F. choke should offer a high impedance to all alternating currents having a frequency lower than 10,000 cycles, but at the same time its resistance to D.C. current should be as low as possible.

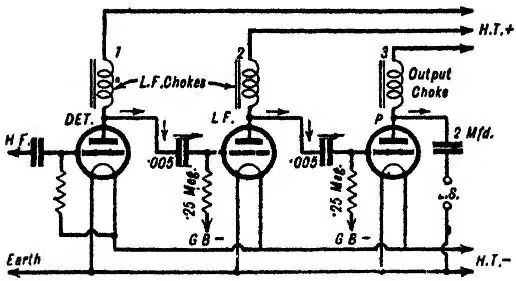


FIG. 18—A CHOKE CAPACITY COUPLED AMPLIFIER.

The chokes in this circuit prevent audio frequency currents from passing into the H.T. circuit. Choke 3 is also used to provide a choke-capacity loudspeaker filter.

Use of L.F. Chokes

L.F. chokes are employed principally for coupling together low-frequency valves in the manner indicated in Fig. 18. The object of the two chokes marked " 1 " and " 2 " is to feed the high-tension supply to the anodes of the first two valves, though preventing the audio (speech and music) frequencies from passing into the H.T. circuit. The audio frequencies are in fact diverted along the paths indicated by arrows.

The purpose of the two 0·005 mfd. condensers is merely to prevent the steady anode potential being applied to the grids of the low-frequency valves, whilst the 0·25 megohm grid leaks serve to apply suitable values of negative grid bias.

The values of condensers and grid leaks are not critical, but those indicated are average ones.

Choke-capacity Coupling

Choke-capacity L.F. coupling is not used very extensively at the present time although it was more popular a few years ago. The reason for its fall in popularity is that the choke does not, in itself, give any voltage amplification as does the more popular L.F. transformer. In consequence, the only amplification obtained is that of the valves themselves.

There is one point we have not yet considered—a connection to earth is made from one terminal on the choke. The latter terminal is connected internally to the metal core and the earth connection often tends to improve stability. Some makes of choke are not provided with an earth terminal, but in such cases it is generally possible to make connection to one of the core clamping bolts if necessary. One or two manufacturers connect the metal screw eyelets to the core so that the latter may be earthed from a holding-down screw.

Having decided to make a choke capacity amplifier the question arises as to what type and inductance of chokes are necessary.

Let us first consider the choke required for position "1" in Fig. 18. Now the full amplification of the preceding valve can only be obtained if the choke offers an impedance of at least twice that of the valve at all frequencies. And since the impedance of any choke is proportional to the frequency of the current applied to it, we must ensure that the choke will be of ample inductance at the lowest frequency at which full amplification is required. (If the inductance became less than the amount stated at any frequency full amplification would not be given to signals of that frequency.)

Inductance and Frequency

For most practical purposes the lowest frequency at which full response is required is about 50 cycles per second. Assuming the impedance of the detector valve in Fig. 18 to be, say, 12,000 ohms, the choke must therefore offer an impedance of 24,000 ohms (twice 12,000) at 50 cycles.

The equation connecting inductance and impedance is :—

$$\text{Inductance (in henries)} = \frac{\text{Required Impedance (in ohms)}}{2\pi f}$$

where π takes its usual value of 3·14 and f represents the frequency.

Substituting our predetermined values in this equation we find that the inductance should be $\frac{24{,}000}{2 \times 3{\cdot}14 \times 50}$, which cancels out to approximately 80 (henries).

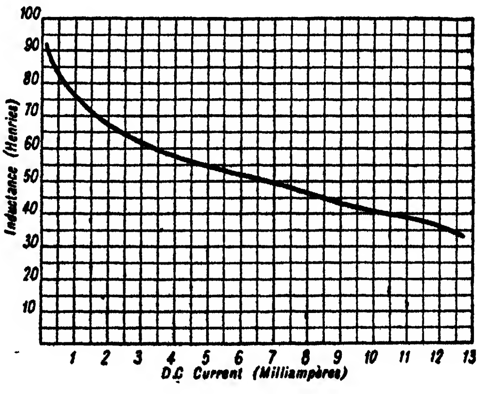


Fig. 19—A Typical Curve showing how the Inductance of a Choke varies with the Current Passing Through its Windings.

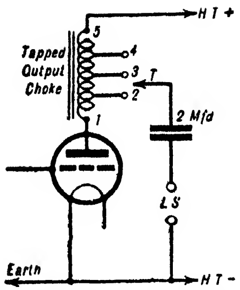


FIG. 20.—A TAPPED CHOKE FOR MATCHING THE SPEAKER TO THE OUTPUT VALVE.

Different ratios are obtained by connecting "T" to tappings 1, 2, 3 and 4.

Inductance and Current

We have now established the fact that choke "1" should have an inductance of at least 80 henries if we are to get full response down to 50 cycles. There is still another point to consider because the inductance of a choke varies not only with the frequency of the alternating currents, but also with the amount of direct current passing through its windings. For example, a choke rated at 80 henries might actually have such an inductance when passing an infinitely small D.C. current, but the inductance would probably drop to half that value if the current were increased to, say, 10 milliamperes; this point will be more easily understood by referring to the typical "Inductance — D.C. Current" curve in Fig. 19. It will be clear, therefore, that a choke must be chosen which has a suitable inductance *when passing the required amount of anode current* (that consumed by the preceding valve). Particulars regarding the inductance under varying conditions of current are now supplied by most manufacturers of repute.

The correct inductance for choke "2" in Fig. 18 can be calculated in the manner just outlined by taking into consideration the impedance of the first L.F. valve. The output choke (marked "3") shown in Fig. 18 performs the same function as chokes "1" and "2" but is used to provide a choke-capacity loudspeaker filter.

A filter of this kind is useful in isolating the loudspeaker from the high tension supply. By so doing it saves the speaker from damage which might result from the passage of too great a current through its windings and also obviates the possibility of receiving a shock when touching the speaker terminals. This latter is of especial significance when the receiver is mains-operated. The system has other advantages and enables the full output to be obtained from the last valve by choosing the choke so that it has twice the impedance of the valve—the calculation is just the same as for chokes "1" and "2."

Advantages of Choke Output Filter

An advantage which is of particular importance when the speaker is situated at a distance from the set is that a single connecting wire may be used. This is because one side of the speaker is connected to earth and the earth connection can be made at any convenient point near the speaker. When the speaker is used in the garden, for instance, it is sufficient to drive a short spike into the ground.

The advantage is not concerned merely with the economy of wire that may be effected, but it has a bearing on the quality of reproduction. When a fair length of twin wire is used to connect the speaker there is an appreciable capacity between the wires and this causes a certain loss of strength on high notes.

The output choke just referred to acts as a 1 : 1 output transformer and, in consequence, the speaker will only be correctly matched to the last valve when it has an impedance equal to twice that of the valve. At least that is true in theory, but in practice it is found that considerable latitude is permissible, without making any sacrifice in efficiency, when a three-electrode valve is employed in the output stage, although conditions are fairly critical in the case of a pentode.

Tapped Output Chokes

When using a pentode or when the speaker impedance varies considerably from the correct figure a " step-down " effect must be obtained between the valve and speaker. The step-down could be effected by means of a transformer, but it can also be produced by using a tapped choke as shown in Fig. 20.

The choke shown has three equidistant tappings and can be made to provide four alternative ratios. By connecting tappings

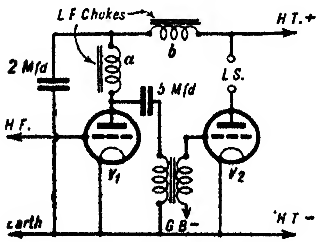


FIG. 21.—HOW LOW-FREQUENCY CHOKES CAN BE USED TO REPLACE RESISTANCES.

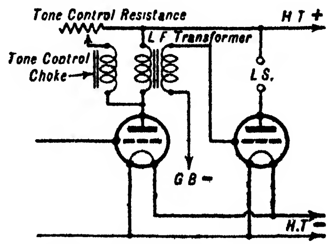


FIG. 22.—USING A LOW-FREQUENCY CHOKE AS A MEANS OF EFFECTING TONE CONTROL.

" T " to terminal 1 the ratio is 1 : 1, taking it to terminal 2 increases the ratio to 3 : 1, whilst moving it to terminals 3 and 4 alters the ratio to 2 : 1 and 4 : 1 respectively. It will have been gathered that the ratio is represented by the proportion between the total number of turns on the whole winding and those between terminal 5 and the tapping output.

Matching the Loudspeaker

Before leaving this subject it should be explained that the correct output ratio is found from the equation :—

$$\text{Ratio} = \sqrt{\frac{\text{Optimum load of valve.}}{\text{Impedance of speaker.}}}$$

The " optimum load " is equivalent to twice the impedance for three-electrode valves, but is a different factor in the case of pentodes. Incidentally, the optimum load for both power and pentode valves is generally stated on the makers' instruction sheets.

Chokes in place of Resistances

It is not generally realised that low-frequency chokes can be employed to replace resistances in most A.C. circuits. An example of this is given in Fig. 21. Choke " a " takes the place of the more usual resistance employed for " resistance-feeding " the L.F. transformer. Its correct value can be found in exactly the same way as explained in reference to Fig. 18.

Choke " b " serves as a de-coupling resistance and operates in conjunction with the 2 mfd. condenser. This component may have an inductance similar to that of " a."

Low-frequency chokes would be eminently suitable for the purposes indicated and would be very valuable where high-tension voltage was at a premium. Naturally the chokes would be much more costly than resistances and their use could only be recommended in the case of a very limited supply of high-tension voltage.

Tone Control Chokes

There is another use for L.F. chokes which we have not yet considered ; that is in connection with tone control circuits.

A tone control choke can be connected in numerous ways and the simplest is shown in the circuit of Fig. 22. The choke is connected, through a variable resistance, in parallel with the

primary winding of the L.F. transformer. The impedance of the primary winding is reduced by putting the choke in parallel with it and, in consequence, the response to low notes is reduced; low-note attenuation produces an effect equivalent to increased high-note response.

The effect of the parallel-connected choke is reduced by increasing the amount of resistance in circuit and therefore the variable resistance makes possible an even regulation in tone.

Smoothing Chokes

Chokes used for smoothing purposes in high-tension supply circuits are similar in principle and construction to low-frequency chokes, but their method of operation is quite different.

Let us consider the smoothing circuit shown diagrammatically in Fig. 23. Now the voltage supplied to it from the D.C supply (mains or A.C. rectifier) is not of constant value, but fluctuates rapidly within certain limits. If the fluctuating voltage were applied to the anodes of the receiver valves it would cause a note to be produced in the loudspeaker and that would obviously spoil reception.

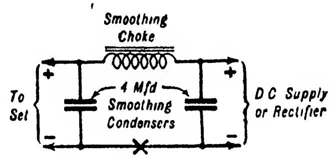


FIG. 23.—DIAGRAM OF A TYPICAL SMOOTHING CIRCUIT.

It will be seen that the smoothing circuit consists of two condensers in shunt with the supply, and an iron-cored choke in series with the positive lead.

The condensers do a fair amount in respect to smoothing due to their ability to "store" electricity. Briefly, their function is to "absorb" electricity when the fluctations cause the voltage to rise above the mean figure, and to discharge some of their stored-up energy when the voltage falls below the mean.

If we may draw an analogy, smoothing condensers can be likened to the road springs of a motor vehicle; the springs "give" and "take" as the wheels traverse a bumpy road and so the tendency of the body of the vehicle is to keep in the same horizontal plane.

But the springs would not be effective if the body of the vehicle were of very light weight in comparison with the strength of the springs. It is partly due to the inertia (resistance to change of motion) of the body that the springs are effective.

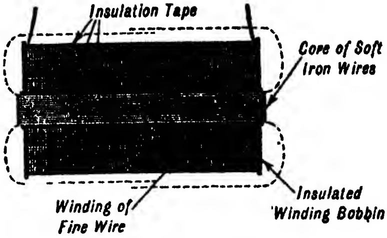


FIG. 24.—SECTION THROUGH A LOW-PRICED CHOKE.

If we continue our analogy we can say that the object of the choke is to introduce a certain amount of "inertia" into the electrical system.

It is not difficult to see how the choke does this if we remember that the core becomes magnetized due to the current passing through the windings. Any change in current causes a change in the state of magnetism; thus a sudden increase in current would cause an increase in magnetic flux. But the latter creates a voltage (more correctly an electro-motive force) which acts in opposition to the normal current flow and this tends to counteract the sudden voltage increase. The net effect of the choke is to keep the current flowing through it at constant intensity.

Inductance of Smoothing Choke

The correct inductance for a smoothing choke cannot be calculated so easily as can that of an L.F. choke and in practice it is generally determined by experiment.

Knowing that an average value for a high-tension smoothing choke is about 25 henries we can get some idea of the correct value by studying the nature of the current supplied to it. When the latter is obtained by rectifying 50 cycle A.C. on the half-wave principle, the fluctuations will occur at the rate of 50 cycles per second and the 25-henry choke will in all probability be adequate. If, however, the 50 cycle A.C. is rectified by the full-wave method the fluctuations will be twice as frequent (100 per second) and a choke of lower inductance will be able to cope with them.

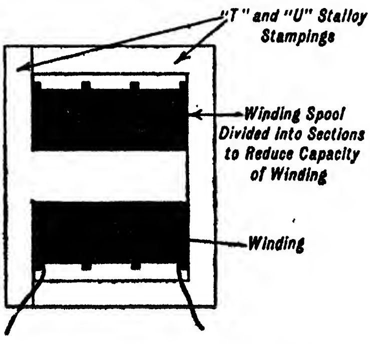


FIG. 25.—SECTION THROUGH A L.F. OR SMOOTHING CHOKE OF USUAL PATTERN.

When the supply is from 25 cycle mains the "fluctuation frequency," as one might call it, will be only half as great, and

in consequence twice the inductance will be required to produce the same amount of smoothing. In such cases, a single choke might be insufficient and a second one would be required at the point indicated by a cross in Fig. 23.

The above rules apply principally to rectified A.C. current, but have equal significance in regard to D.C. although the fluctuation frequency of D.C. is generally not known and so the required inductance value must be determined purely by experiment.

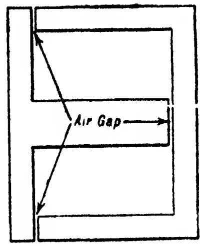


FIG 26—HOW THE STAMPINGS ARE ARRANGED IN A "GAPPED CORE" OR "CONSTANT INDUCTANCE" CHOKE.

It will be clear from what was said in reference to L.F. chokes that the inductance of smoothing chokes must also be determined in relation to the amount of current involved.

Gapped Core Chokes

Although it has been stated that the inductance of the usual types of chokes (such as those shown in section in Figs. 24 and 25) varies with the current passing through the windings, it is possible to construct a choke with a constant inductance regardless of current.

Such a choke is made as shown in Fig. 26, a small air gap being left in the circuit of the core. The gap causes a slight reduction in the effectiveness of the core and makes it necessary to use a greater number of turns for the windings. The use of gapped core chokes is more or less confined to experimental and " power " purposes although the chokes *are* used in making eliminators and mains sets of the larger kinds.

The Construction of Iron Core Chokes

Up to now we have dealt with the uses of L.F. and smoothing chokes, but we have said very little with regard to their construction. The simplest type of L.F. choke is that shown in Fig. 24. It has a core consisting of a bundle of soft iron wires, and this is fitted into a wooden, Bakelite or fibre bobbin in which the windings are placed. The latter usually consists of several thousands of turns of fine gauge wire divided into sections by layers of insulating tape. By splitting up the windings in this way, capacity is reduced.

The "open" core is not very efficient, but efficiency can be increased by employing a "closed core," that is, one in which there is a continuous magnetic circuit. This can be provided by allowing the iron wires to project at each end of the bobbin and then bending them back over the bobbin so that the two ends meet each other, as shown in broken lines in Fig. 24.

Closed Core Chokes

The most common type of choke for either L.F. coupling or smoothing, however, is that shown in section at Fig. 25.

The core is made up from "T" and "U" shaped laminations of Stalloy, and they are interlocked to form a closed magnetic circuit. The "Stalloy" is more efficient than ordinary iron and does not cause so much efficiency loss. A number of laminations are used in preference to a solid core because it is found that magnetism does not penetrate very deeply into a large mass.

D.C. Resistance

The question of D.C. resistance has been left until last. In the case of a choke for L.F. coupling it is of little consequence, but with a choke used for a loudspeaker filter or for smoothing, a high resistance can be very troublesome.

The principal difficulty caused by high resistance is that it entails a voltage drop which cannot generally be afforded. The reason will be obvious when it is realized that a choke of 2,000 ohms D.C. resistance will "drop" 100 volts when used for smoothing a 50 milliampere supply.

Of course we are bound to have some D.C. resistance and for average purposes a resistance of 700 ohms should not be considered excessive. When there is very little voltage to spare, lower resistance chokes, down to 200 ohms or so, can be obtained, but these are fairly expensive. When designing an all-mains receiver or an eliminator one should not forget to make allowances for the voltage drop which must inevitably be created by the smoothing choke or chokes.

CHAPTER VIII

TRANSFORMERS

EVERY experimenter is well acquainted with transformers of several kinds. They are so named by virtue of their function which is to "transform" the electrical impulses supplied to them, so that either the voltage or the current is increased.

Input and Output Circuits

The transformer has two circuits, the input circuit where the electrical energy is fed into the device, and the output circuit across the terminals of which the transformed energy is available. The transformer proper comprises an arrangement of inductance with induction coupling between the input and the output circuits. Usually the coupling is by the mutual induction between two coils, and this mutual induction causes the energy transfer from input to output circuit. It will be evident from this that only energy due to alternating current can be passed through a transformer, since steady direct current energy does not create an induction effect. A direct current of varying intensity is equivalent to a combination of direct and alternating currents, and hence can be classed as an alternating current, for the purposes of its action in relation to a transformer.

We have stated that the transformer amplifies *either* the voltage or the current. It cannot amplify both. This may be shown as follows. The power in an electrical circuit is measured by the product of the voltage E across the circuit and the current I in the circuit, or writing P as shorthand for power, we have :—

$$P = EIk \qquad (1)$$

The power is in *Watts* when E is in volts and I is in amperes ; k is a number with a value between 0 and 1.

Power Factor

For D.C. circuits $k = 1$: in the case of A.C. circuits, k is called the POWER FACTOR of the circuit, and its greatest value is 1. The smaller k is the more power is wasted in the circuit. It is the object of designers of A.C. electrical apparatus to make the circuit efficient so that $k = 1$, or is nearly equal to 1. The circuit is then highly efficient. In A.C. circuits E and I are R.M.S. values of voltage and current, and not peak values. In the case of an A.C. valve filament circuit where there are three valves each taking 1 amp. of current at 4 volts, the power in the circuit is:

$$P = 4 \times 3 \times k \text{ watts.}$$

Such a circuit is usually highly efficient, and so, putting $k = 1$, we have :—

$$P = 12 \text{ watts.}$$

Now consider a transformer in which the input power is P, comprising voltage E across the input terminals and current I in the input circuit. Let the power factor be k. Then the relation (1) holds. Now suppose that the output voltage is $n \times E$, where n is greater than 1. Then the voltage has been amplified n times. Thus if the input voltage is 100 volts, and the output voltage is 240 volts, the voltage has been amplified 2·4 times—*i.e.*, $n = 2{\cdot}4$ in this case.

Input Losses

It is one of the principles of science that energy of any sort cannot be created, magically, as it were. The power obtained from a machine (mechanical or electrical, etc.) can never be greater than the power put into the machine. Usually the machine is inefficient and wastes a considerable amount of the input energy, so that only a certain percentage is available at the output end. In a very well designed machine the losses can be made very small, and we shall suppose that in the case of the transformer we are treating now there is no energy loss between input and output. If the input power be 50 watts, then the output power is also 50 watts. Thus the output power of this transformer is P, and the power factor of the output power is

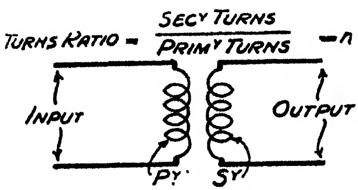


FIG. 1.—A TRANSFORMER WITH TWO COILS VERY CLOSE TOGETHER.

assumed to be the same as that of the input, viz., k. Let us write i for the output current, then we have :—

$$\text{Output power} = P = nE \times i \times k,$$

i.e.,
$$\frac{P}{nEk} = i \quad . \quad (2)$$

Writing in the value of P from (1) we have :—

$$\frac{EIk}{nEk} = i$$

Cancelling the E and the k on the left-hand side we have :—

$$\frac{I}{n} = i \quad . \quad (3)$$

In other words, when the voltage is amplified, or stepped-up, n times, the current is "de-amplified," or stepped-down, n times. The same reasoning shows that when the current is increased the voltage is decreased. In the case just considered, if the input current be 4·8 amps., the output current will be $\frac{4\cdot8}{2\cdot4}$ amps., or 2·0 amps.—*i.e.*, the current is stepped down 2·4 times.

Turns Ratio

In the case of transformers of the type illustrated in Fig. 1, where the two coils are very close together, the voltage step-up—*i.e.*, $\frac{E_s}{E_p}$, where E is the voltage and the subscript denotes primary and secondary—is equal to the ratio of the number of turns of wire on the secondary coil to the number of turns on the primary coil.

i.e,.
$$\frac{E_s}{E_p} = n \quad . \quad . \quad (4)$$

where n is the TURNS RATIO of the transformer.

Equation (4) can be expressed in the form

$$\frac{E_s}{E_p} = \frac{T_s}{T_p} \quad . \quad . \quad (5)$$

and the current ratio will be

$$\frac{I_s}{I_p} = \frac{T_p}{T_s} \quad . \quad . \quad (6)$$

where I_s and I_p are secondary and primary currents respectively,

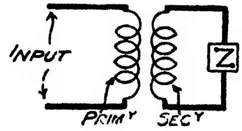


FIG. 2.—EFFECT WHEN THE TRANSFORMER IS CONNECTED IN A CIRCUIT.

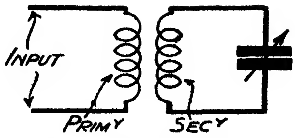


FIG. 3.—SECONDARY WINDING TUNED BY A CONDENSER.

and T_s and T_p the number of turns on the secondary and primary windings.

The current ratio can also be expressed as

$$I_p T_p = I_s T_s \quad . \quad . \quad (7)$$

i.e. the primary ampere-turns are equal to the secondary ampere turns.

Mutual Induction

It is important to note here that both the primary and secondary windings of the transformer possess self-inductance, and a mutual inductance exists between the two coils. When the transformer is connected in a circuit the effect on the transformer is as if an impedance or a pure resistance is connected across its secondary winding (see Fig. 2). Now since the mutual induction effect is *mutual*—*i.e.*, it operates from primary to secondary, and *vice versa*—the *effect* of the secondary load Z is conveyed into the primary circuit, the reason being that by Lenz's Law the secondary current opposes the primary current, tending to demagnetize the coil.

In Fig. 2 the secondary load Z may take several forms, such as a valve filament, in the case of a mains transformer, or the speech coil winding of amoving-coil loudspeaker, in the case of an output transformer of a receiver, or it may be due to the fact that the secondary winding is tuned by a condenser (as in Fig. 3) as occurs in the case of transformers used for coupling the various radio-frequency and intermediate frequency amplifier stages of a receiver. In this last case, the secondary impedance is what is known as the DYNAMIC RESISTANCE of the whole tuned circuit.

Input Impedance

A matter of some interest is the input impedance, with the ideal arrangement the primary takes no current if the secondary is unloaded. Actually a practical transformer takes a small

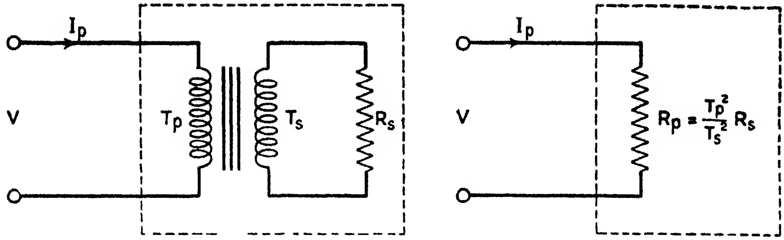


FIG 4 —IDEAL TRANSFORMER
The figure on the right illustrates the input resistance

magnetizing current because it operates as a simple inductance, usually having a large value—such as 20H or more. When the secondary is loaded on a resistance R_s,

$$E_pI_p = E_sI_s \text{ nearly, } = I_s^2R_s = I_p^2(T_p/T_s)^2R_s$$

so that $$E_p = I_p(T_p/T_s)^2R_s$$

and $$E_p/I_p = (T_p/T_s)^2R_s$$

But E_p/I_p is the ratio of the input voltage and current, which is the impedance that the primary offers to the supply. It is seen to be

$$\frac{E_p}{I_p} = R_p = \frac{(T_p)^2R_s}{(T_s)} \quad . \quad . \quad (8)$$

Thus the primary acts as if it were a resistance equal to that of the secondary load multiplied up by the square of the turns-ratio. If the transformer with its secondary load were put into a box it would be indistinguishable from a simple resistance of

$$R_p = (T_p/T_s)^2R_s \quad . \quad . \quad (9)$$

connected across the input terminals (Fig. 4).

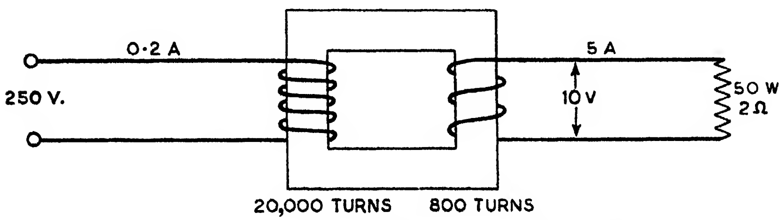


FIG 5 —EXAMPLE OF TRANSFORMER CALCULATION.

Example.—A transformer, Fig. 5, comprises a primary with 20,000 turns and a 800-turn secondary. What will be the power dissipated in a 2-ohm resistor connected across the secondary terminals, and what will be the effective primary input resistance? The primary is connected to a 250 volt supply.

The secondary E.M.F. is $E_s = 250 \times 800/20{,}000 = 10$ volts and the secondary current $I_s = 10/2 = 5$ amps. The secondary power is $E_sI_s = 10 \times 5 = 50$ watts. The primary current is $I_p = I_sT_s/T_p = 5 \times 800/20{,}000 = 0{\cdot}2$ amps, and the ratio $E_p/I_p = 250/0{\cdot}2 = 1{,}250$ ohms. This will be seen to be the same as $R_s(T_p/T_s)^2 = 2(20{,}000/800)^2 = 1{,}250$ ohms.

Types of Transformers

There are two main types of transformers used in radio work:—

(1) Those used for circuits in which the frequency of the current is fixed (*e.g.*, mains transformers).

(2) Those used in circuits where several different frequency currents are passing.

Of the latter type there are two important sub-divisions: (*a*) those used in circuits in which one current of one frequency passes at a time—*i.e.*, radio-frequency transformers dealing with one radio frequency at a time, and (*b*) those used in circuits which carry currents of several frequencies simultaneously—*i.e.*, AUDIO (or audible) frequency transformers dealing with the range of audible frequencies transmitted from the studio. We shall restrict our attention to considering some of the features of audio-frequency transformers.

The relation (4) is only approximate in the case of audio-frequency transformers, and a variety of other factors have to be taken into consideration. One of the chief of these is the effect of the iron core on which the transformer is assembled. Other important factors are the capacity between the two windings and the manner in which the primary and secondary coils are wound —*i.e.*, whether wound in one or more sections, and whether placed next to each other or on top of each other, and so on.

Frequency Distortion

The well designed transformer gives approximately constant amplification at all frequencies. This is necessary in order that certain notes shall not be emphasized relative to others, resulting

in distortion of the music—not necessarily distortion which is disagreeable to the ear, but nevertheless, distortion in as far as the original balance between the notes in the studio is not being preserved. The emphasizing or attenuating of a note of one frequency relative to a note of another frequency is known as FREQUENCY DISTORTION. Thus in the case of, say, a 1 : 5 voltage step-up transformer, the ideal is that every signal voltage, whatever its frequency, shall be amplified 5 times. Frequency distortion is present if voltages of one frequency are amplified 5 times, and voltages of other frequencies amplified more or less than 5 times.

Amplitude Distortion

Another form of distortion which can occur in audio-frequency transformers is the distortion of notes of the same frequency. The term AMPLITUDE DISTORTION is used to describe this form of distortion. Suppose a note of a certain frequency is represented in the transformer circuit by an alternating current signal of maximum amplitude of, say, 5 volts. If the performer in the studio now produces a note of twice the amplitude, the transformer should now be handling a signal of amplitude 2 × 5 volts, or 10 volts. If the new signal amplitude is not twice the original value, but some other value, then distortion has occurred. (Both of these forms of distortion may occur in parts of a receiver other than the audio-frequency transformers.)

Amplification Curves

The actual amplification obtained with a particular transformer depends very largely on the type of valve with which it is used. In view of this it is usual to express the record of the performance of an audio-frequency transformer in the form of a curve showing the total amplification obtained from the complete unit comprising valve and transformer. We shall refer to this again. Such a curve is reproduced in Fig. 6, and it will be seen that the frequency scale is not equi-spaced but is a logarithmic scale. This enables the whole range of audible frequencies from about 20 cycles per second to 10,000 cycles per second to be covered on a reasonably small size of graph paper.

The graph was obtained by measuring the output voltage at different frequencies. The input voltage, at all frequencies, was maintained the same. The fact that the curve is not a straight

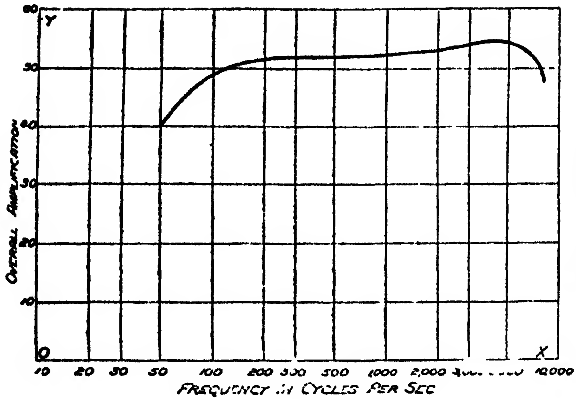


FIG. 6.—CURVE SHOWING TOTAL AMPLIFICATION OBTAINED FROM THE COMPLETE UNIT COMPRISING VALVE AND TRANSFORMER.

line parallel to the OX axis shows that notes of the same initial amplitude but of different frequency have different amplitudes when they have passed from input to output circuits. That is to say, frequency distortion has occurred. The extent of the *effect* of frequency distortion shown by the curve depends on the sensitivity of the ear to changes in intensity of musical notes. The response of the ear to sounds is an important factor governing the accuracy of the reproduction required from a radio receiver or radio gramophone, and we must refer to the matter briefly.

Sensitivity of the Human Ear

The ear behaves in a manner which is characteristic of the behaviour of all the senses. It is not sensitive to a fixed definite change in intensity of sound. Instead, it is sensitive to a fixed *percentage change* in intensity. Thus, a change in intensity from 20 to 21 units of sound intensity represents a change of 1 unit, or a percentage change of 5 per cent. This is not sufficient to be perceived by the ear. A change from 2 to 3 units is also a 1-unit change, but the percentage change is 50 per cent., a change which is easily detected. The sensitivity of the ear varies widely from person to person, and it would be quite wrong to speak of an *average ear*, but as a rule it is generally accepted that the ear can scarcely perceive a 20 per cent. intensity change, and can appreciate a 25 per cent. change. The variation shown by the curve of Fig. 6 is, of course, an amplification variation, and does not indicate, directly, intensity variations.

Expression of Electrical Power

When we discuss the ear's response to sounds we are referring to its response to actual sound waves. These waves come from the loud speaker and are due to the electrical signals in the receiver. The intensity of a sound wave is its power and this, corresponds exactly to the electrical power in the receiver circuits. Thus, the figures just given for the ear's sensitivity are true for electrical power in the receiver as well as for sound intensity, provided that the loud speaker does not introduce amplitude distortion. We have already seen that the power in an electrical circuit can be expressed in terms of the current and voltage of the circuit. There are two other ways of expressing electrical power which are often used in power calculations. For the two cases of a D.C. circuit, and of an A.C. circuit comprising pure resistance only—*i.e.*, $k = 1$—it can be shown that :—

$$P = EI \text{ as before in equation} \quad (1)$$

also $$P = \frac{E^2}{R} \quad . \quad . \quad . \quad . \quad (10)$$

and $$P = I^2 R \quad . \quad . \quad . \quad . \quad (11)$$

where R is the resistance of the circuit in ohms. As before, P is in watts, I in amps, and E in volts. These three formulæ are identical and it is usual to use the one which is most convenient in practice.

APPLICATIONS OF AUDIO-FREQUENCY TRANSFORMERS

An audio- or low-frequency transformer is normally used to couple together two amplifying valves. Its object is to provide a step-up or increase in voltage. The primary has fewer turns than the secondary and the proportion between the numbers of primary and secondary turns is referred to as the transformer ratio.

For instance, if there were 10,000 turns (a fairly average number) on the primary and 40,000 on the secondary, the transformer would be said to have a 4 : 1 ratio. Theoretically the voltage step-up afforded is equal to the ratio as already explained, so that if a voltage (of audio-frequency current) of 2 were applied

to the primary winding, 8 volts would be developed across the ends of the secondary.

In practice, the actual voltage step-up ratio is not quite equal to the turns ratio because of the resistance of the windings, imperfections of the core and so on, as we have already explained.

A skeleton circuit of a typical transformer-coupled amplifier is given in Fig. 7. When buying a transformer for such a circuit one should always obtain a component which has a high primary inductance when carrying the necessary amount of anode current.

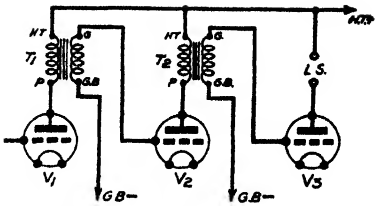


Fig. 7.—Skeleton Circuit of a 2-Stage Transformer Coupled Amplifier.

Parallel Feed

A good method of connecting a transformer is in the manner shown in Fig. 9. In this case, the resistance R carries the full D.C. anode current of V.1 and the transformer has thus to deal only with the audio-frequency currents which are passed on to it by the coupling condenser C. This system of transformer connection is referred to as a parallel feed or resistance feed due to the fact that the primary winding is virtually in parallel with the resistance, and the anode current is fed through the latter instead of through the transformer.

Since the primary winding of the transformer has not to deal with the steady anode current of V.1 its inductance maintains a maximum value and there is no possibility of the core becoming saturated. In consequence, quite a small and inexpensive transformer can be made to give satisfactory response to the very lowest frequencies.

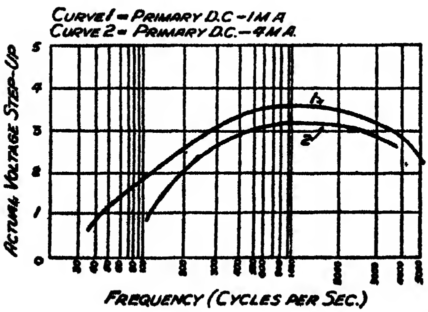


Fig. 8.—Performance Curves for a Typical Medium-Priced Transformer when Passing Different Values of Primary D.C.

The value of R (in ohms) must be about twice the impedance of V.1 and the capacity of C must be large enough to provide an easy path for all audio-frequency

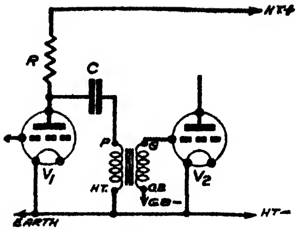


FIG. 9.—A LOW-FREQUENCY TRANSFORMER USED IN A RESISTANCE-FEED, OR PARALLEL-FEED CIRCUIT.

currents; a capacity of from ·25 to 1 microfarad is generally employed. With this form of coupling, the actual step-up ratio of the transformer is very nearly equal to the turns ratio.

L.F. Coupling Units

In order to simplify the use of resistance feed, L.F. coupling units are available which combine a transformer, resistance and condenser. The resistance normally has a total value of 50,000 ohms but is tapped at 30,000 ohms so that either value can be employed at will. The lower value is suitable for use after valves having an impedance of some 15,000 ohms or less, and the higher value is appropriate to all valves up to 25,000 ohms.

A practical point which is worth remembering is that when the 30,000 ohm portion only of the resistance is used for its legitimate purpose the remaining (20,000 ohms) part can be used for decoupling by connecting a 2 mfd. condenser between the tapping and earth. Fig. 10 will make this explanation quite clear.

It is interesting to notice that when using an ordinary transformer in a parallel-feed circuit a number of alternative step-up ratios can be obtained by altering the connections to those given in Figs. 11A, B and C. The connections shown in Fig. 11A are those already described and the ratio obtained is the nominal one; for purposes of comparison let us call it 4 : 1. By altering the connections to those shown in Fig. 11B, that is by putting primary and secondary in series and joining one side of C to the junction, the ratio becomes 5 : 1, or that of the total number of turns on both windings to the number of turns on the primary. When the connections are changed to those shown in Fig. 11C the ratio is reduced to 1 : 1. Although a transformer is employed, the methods of coupling shown in

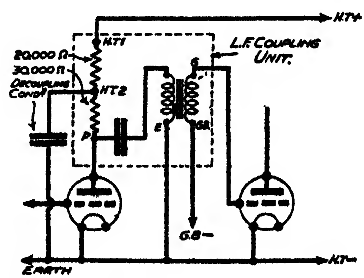


FIG. 10.—USING A PORTION OF THE RESISTANCE IN A LOW-FREQUENCY COUPLING UNIT FOR DE-COUPLING THE ANODE CIRCUIT OF THE PRECEDING VALVE.

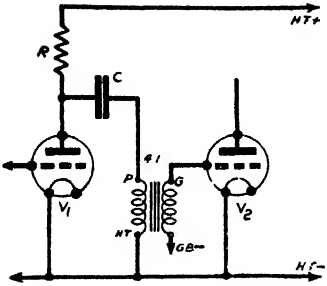


FIG. 11A.—THE RESISTANCE-FEED SYSTEM

This circuit gives a 4 to 1 step-up ratio.

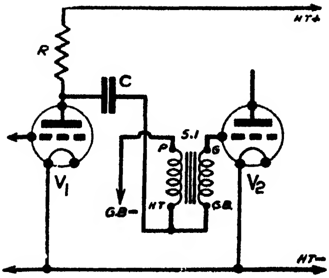


FIG. 11B.—THE RESISTANCE-FEED SYSTEM.

This circuit gives 5 to 1 step-up, ratio.

Figs. 11B and 11C are known as "autochoke" because, since the windings are in series, the transformer really acts as a tapped choke.

Tone Control Transformers

When very selective tuning circuits are employed they cause a definite loss of high-note amplification. To counteract this we must so adjust our L.F. circuits that they will give additional amplification to the higher notes, and as a result make all notes of equal intensity by the time they reach the loud speaker.

Various forms of correction devices can be employed for this purpose, but the simplest is the tone control transformer. As a matter of fact we cannot actually give extra amplification to high notes, but we can, and do, achieve the equivalent result by curtailing low-note amplification.

This is done by using a transformer fitted with a small L.F. choke, which can be connected in parallel with the primary winding through a variable resistance, as shown in Fig. 12. The tone-control choke and variable resistance are themselves in series and the two are put in parallel with the primary winding. The choke

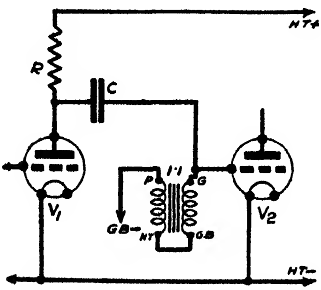


FIG. 11C.—THE RESISTANCE-FEED SYSTEM.

This circuit gives a 1 to 1 step-up ratio.

has the effect of reducing the primary inductance and so lessening its response to low frequencies. As the amount of resistance in circuit is increased, the effect of the choke is reduced and so low-note amplification can be brought up to its normal level if desired.

The type of tone control transformer just described can only operate in the desired manner when the rest of the circuit is designed to emphasize low-note response. Its use is therefore limited and it would not confer any advantages to a flatly tuned set or one fitted with band-pass tuning. Similarly, it would probably be of little use if the set were used as an amplifier with a pick-up.

As a matter of fact, additional low-note amplification would most probably be required in the latter cases and consequently the transformer should give just the opposite effect to the type described.

Suppressing either High or Low Notes at Will

For this reason another type of tone control transformer has been developed with which either low or high notes can be suppressed at will. This, of course, gives the equivalent effect to providing additional high- or low-note amplification. The circuit arrangement is shown in Fig. 13. It will be seen that besides the transformer and L.F. choke a fixed condenser is also provided. One side of both the choke and condenser are joined to one end of the transformer primary and the other sides are connected one to each end of a high-resistance (·25 megohm

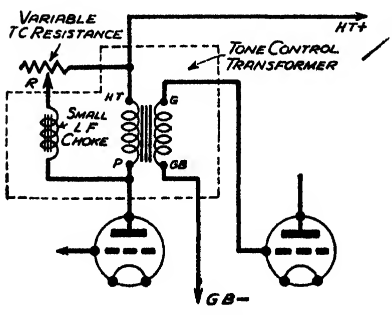


FIG. 12.—CONNECTIONS FOR A TONE CONTROL TRANSFORMER USED FOR SUPPRESSING LOW-NOTE AMPLIFICATION.

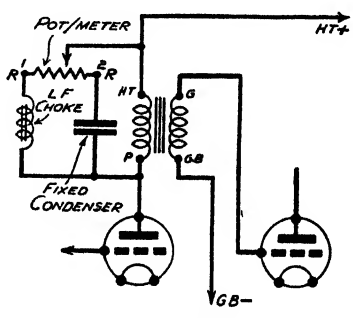


FIG. 13.—A TONE CONTROL TRANSFORMER OF THE TYPE SHOWN HERE CAN BE USED TO REDUCE EITHER HIGH OR LOW-NOTE AMPLIFICATION.

upwards) potentiometer of which the slider is connected to the other end of the primary.

When the potentiometer slider is moved to the end marked "1" the choke is put in parallel with the transformer primary and, in consequence, the inductance of the plate circuit is considerably reduced. As a result, the lower frequencies can leak away across it and so escape amplification. On the other hand, when the potentiometer slider is moved to the end marked "2" the condenser is put in parallel with the primary, and this permits the higher frequencies to leak away. It will be clear that by adjusting the potentiometer between its two limits the degree of high-note or low-note loss can be varied at will.

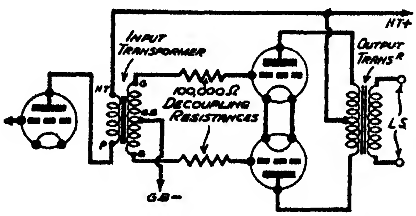


FIG. 14.—SKELETON CIRCUIT OF A PUSH-PULL AMPLIFIER.

If desired, any type of tone control transformer can be connected on the parallel feed system as shown in Fig. 9. As a matter of fact, the three referred to are all capable of carrying a primary current up to 4 milliamps without fear of core saturation, and so it will seldom be necessary to resistance-feed them. If any low-note loss were to result from the passage of a fairly high primary current it could easily be compensated for by adjustment of the control.

Push-Pull Transformers

Our study of L.F. transformers would be incomplete if we were not to consider those specially designed for push-pull amplifiers. A circuit diagram of an amplifier using push-pull is given in Fig. 14.

Two transformers, one input and one output, are used. The input transformer has a primary winding just like that of any other L.F. transformer, but the secondary winding is divided into two halves each of which feeds one valve. The centre tapping takes the grid bias supply for both valves.

The output transformer is the opposite of the input since its primary winding is divided into two halves which "collect" the output from the two valves. The secondary winding is a single

one, but is generally supplied with two or three tappings so that different ratios can be obtained for the purpose of matching the loud speaker to the valves.

Push-pull input transformers are generally a good deal larger (physically) than ordinary L.F. transformers, because being used after other low-frequency valves, their primary windings have to carry a comparatively large D.C. current. At the same time the impedance of the preceding L.F. valve is fairly low and in consequence a low inductance primary winding is permissible. With the best types of push-pull transformers the primary winding of the input transformer will carry up to 10 milliamps, and at that figure shows an inductance of just under 30 henries.

When the preceding valve takes an anode current in excess of 10 milliamps the transformer can be resistance-fed in just the same way as any other type.

In building a push-pull amplifier the two valves used in push-pull should be obtained as a matched pair; if they are not identical in their characteristics a certain amount of instability is likely to occur. As an additional safeguard against the latter trouble it is advisable to insert a 100,000 ohm decoupling resistance in series with the grid lead to each valve as shown in Fig. 14.

The push-pull system of amplification is covered in greater detail in Chapter XVI, which deals with the subject of low-frequency amplification.

Arrangement of Transformers

When building a receiver the disposition of the transformers employed should receive careful attention. In the first place they must be kept well away from the tuning circuits to avoid "pick-up" of H.F. currents from the coils.

To ensure freedom from L.F. instability the transformers should be kept a reasonable distance apart and they should be so arranged that their cores are at right angles. In this respect it is also helpful to earth the iron cores.

When using only a single stage L.F. amplifier it is generally best to choose a transformer with a high ratio (up to 7 : 1 or so) provided that its other characteristics are suitable for the circuit. But a lower ratio component with a high primary inductance will almost invariably give more amplification, as well as better quality, than a transformer with a high ratio and a low primary inductance. It should always be borne in mind that high

primary inductance at the working current is more important than anything else.

In an amplifier having two or more transformer coupled stages it is best to use low ratio transformers unless one is prepared to take elaborate precautions in regard to de-coupling anode and grid circuits. As a general rule, a ratio of from 1 : 1 to 2½ : 1 is most satisfactory when more then two stages are employed, but it is safe to go up to 3½ : 1 in a two-stage amplifier.

If instability is experienced after taking the precautions mentioned, a cure can often be effected by reversing the secondary connections to the last transformer or the primary connections to the first ; the reversal stops L.F. oscillation in the same way as reversing the leads to a reaction coil stops H.F. oscillation.

Another remedy for L.F. instability is to connect a quarter megohm grid leak across the secondary winding of the last transformer. This also has the effect of preventing " shrillness," or over-emphasis of high notes.

CHAPTER · IX

CONDENSERS AND CAPACITY

THERE are two main types of condensers used in all classes of electrical and radio work, viz., fixed condensers and variable condensers, and several subdivisions of type according to design, structure, size, function, and so on. We shall discuss first the different forms of variable condensers used in radio reception for both tuning and reaction circuits.

In the case of a radio receiver, it is necessary to be able to vary the tuning so that signals of different wavelengths or frequencies may be received. This can be accomplished in one of two ways, by varying either the value of the inductance, or the CAPACITY of the condenser, comprising the tuned circuit. The latter course is generally the simpler, and is the course nearly always adopted.

Fig. 1 shows a typical tuning circuit consisting of an inductance L and a variable condenser, or capacity, C, joined in parallel. Let us suppose that this circuit is connected in a receiver. As the capacity of C is increased—*i.e.* as the vanes forming the condenser are interleaved—the wavelength to which the circuit responds is increased. *Thus, the longer the wavelength of the signal we wish to receive, the more capacity we must use in the tuning circuit.*

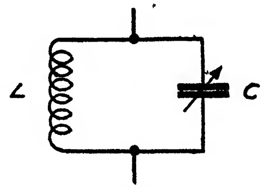


FIG. 1.—A TYPICAL TUNING CIRCUIT.

Consisting of an inductance L, and variable condenser, or capacity C, joined in parallel.

The rate at which the wavelength of the circuit of Fig. 1 increases will depend entirely on the rate at which the capacity of C increases as the tuning dial is rotated. From the point of view of satisfactory reception of broadcasting stations, it is necessary that the capacity shall increase at such a rate that the stations are evenly distributed around the tuning dial. This is the ideal case. In practice, the distribution of stations

around the dial depends on two factors, (1) the wavelength and frequency differences of the stations concerned, and (2) the shape of the moving vanes of the tuning condenser. The shape of the fixed vanes is, in general, quite unimportant, provided that they are large enough to completely overlap the moving vanes when interleaved.

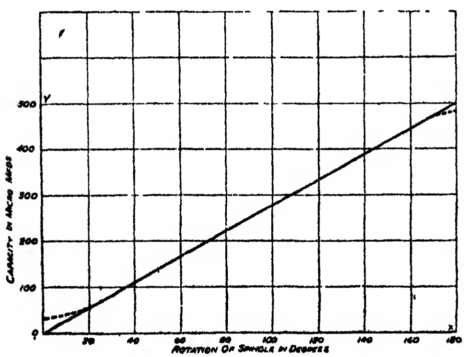
Straight Line Capacity Condenser

In the early days of broadcast reception, variable condensers had semicircular-shaped moving vanes, as shown in Fig. 2A. If we draw a graph showing the *capacity* of such a condenser at each dial reading we shall obtain the straight line of Fig. 2B. It will be seen that the scales used for both axes are equi-spaced scales. In actual practice the graph is not quite a straight line, but curves slightly at each end of the dial reading, as shown by the dotted lines. This type of condenser is still widely employed for reaction circuits, but it is of very little use for tuning circuits, since it crowds the stations together in the first few degrees of rotation.

The name STRAIGHT LINE CAPACITY is sometimes given to this type of condenser to describe the fact that the graph showing the relation between capacity and rotation of spindle is a straight line.

Square Law Condenser

A form of condenser which found very great favour some years ago is the SQUARE LAW, or STRAIGHT LINE WAVELENGTH,



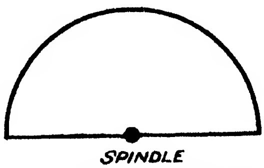


FIG. 2A (*above*).—EARLIEST TYPE OF CONDENSER VANE. With semicircular-shaped moving vanes.

FIG. 2B (*left*).—GRAPH SHOWING CAPACITY OF CONDENSER WITH VANES, AS IN FIG. 2A.

condenser. The usual shape of the moving vanes is shown in Fig. 3A, and it is clear that as the condenser is rotated the area of overlap of the vanes is small at first and greater towards the end of the rotation.

If we employ a condenser of this type in the circuit of Fig. 1 and measure the *wavelength* to which the circuit is tuned at different dial readings, we shall obtain a series of readings which, plotted on a graph, will give the straight line of Fig. 3B. As before, this is the ideal case, and in practice the line curves at each end of the tuning range, as indicated. The effect of this slight curvature is to limit the wavelength range of the circuit.

Straight Line Frequency Condenser

The STRAIGHT LINE FREQUENCY condenser is probably the most widely used type of condenser in many modern receivers. The usual shape of the vanes is shown in Fig. 4A, and Fig. 4B is the graph showing the *frequency* to which the circuit is tuned at each position of the dial. The practical case departs from the ideal as shown by the dotted lines.

Log Law or Log Line Condenser

There is one other type of condenser which is especially suited for use in circuits which are ganged to one tuning control. The shape of the moving vanes is similar to that of the square law condenser. It is known as the LOG LAW or LOG LINE condenser,

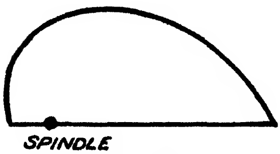


FIG. 3A (*above*).—THE STRAIGHT LINE WAVELENGTH CONDENSER VANE.

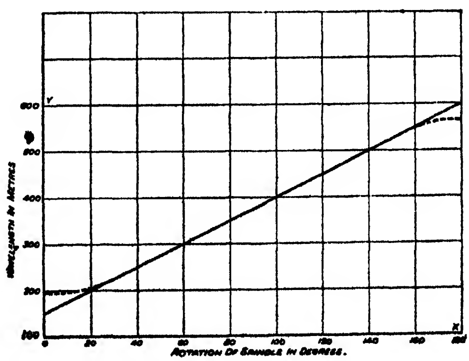
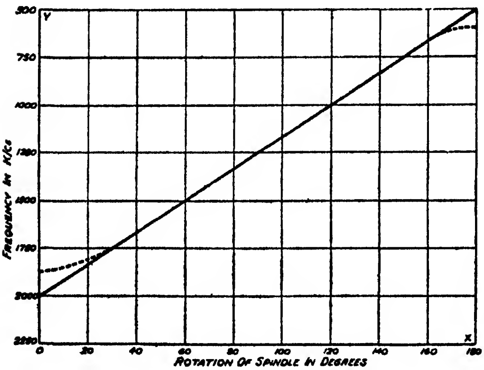


FIG. 3B (*right*).—GRAPH SHOWING CAPACITY OF CONDENSER WITH VANES, AS SHOWN IN FIG. 3A.

and in this case the graph showing the *logarithm of the capacity* against the dial reading is a straight line, as shown in Fig. 5. A logarithmic scale is used for the axis OY, and the values of C are measured along it. This is equivalent to measuring the values of log C along an equi-spaced scale.

Comparison of the Main Types

For easy comparison of the main types, Fig. 6 shows the three shapes of vanes superimposed. The relative sizes of the vanes have been maintained, and the lines joining O to P, Q, R, S, T, U, and V are equi-spaced at 30 degrees. As the vanes are interleaved with the fixed vanes in the direction indicated by the arrow, the area of overlap varies widely for the three types. In the case of the straight line frequency type, in particular, approximately one-half of the total area is enmeshed



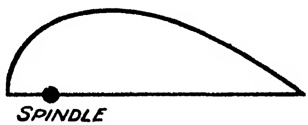


FIG. 4A (*above*).—THE STRAIGHT LINE FREQUENCY CONDENSER VANE.

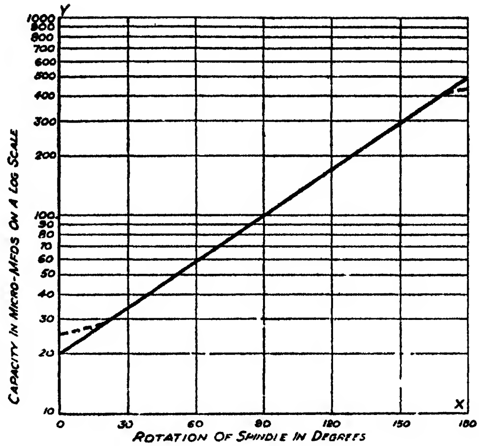
FIG. 4B (*left*).—GRAPH SHOWING FREQUENCY TO WHICH CIRCUIT IS TUNED WHEN USING VANES AS SHOWN IN FIG. 4A.

at the last 30 degrees of rotation, whereas the straight line capacity type enmeshes equal areas for equal amounts of rotation.

We must now consider why the straight line frequency condenser has found great favour with designers of modern receivers. It is well known that broadcasting stations are now separated by frequencies and not by wavelengths. A 9 kc/s. separation —i.e. a frequency difference of 9 kc/s. between each station—is generally accepted as a satisfactory separation under the present crowded conditions of the ether. There are many arguments in favour of a 12-kc/s. separation, but this is quite impossible

FIG. 5.—GRAPH SHOWING DIAL READING AGAINST THE LOGARITM OF THE CAPACITY, WITH A LOG LAW OR LOG LINE CONDENSER.

This type of condenser is especially suited for use in circuits which are ganged to one tuning control.



while there are so many stations distributed throughout the various European countries. The wavelength range from 200 metres to 600 metres is equivalent to a frequency range from 1,500 kc/s. to 500 kc/s., i.e. a range of 1,000 kc/s. With a separation of 9 kc/s., there is room for some 111 stations in this range. Reference to a pre-war list of broadcasting stations in Europe shows that in 1939 there were more than 180 stations, and the result of this congestion was very bad inter-station interference.

According to the official list of frequencies, the more powerful —and hence more easily received—stations are evenly distributed over this frequency range. Hence, in place of the frequency gradations along the axis OY of Fig. 4B we could have written the names of these stations. The other types of condenser cause the stations to be more crowded towards the lower end of the scale. It will be clear, of course, that, in the case of the log law condenser, considerations of ganging outweigh the fact that slightly uneven station distribution is obtained with this condenser.

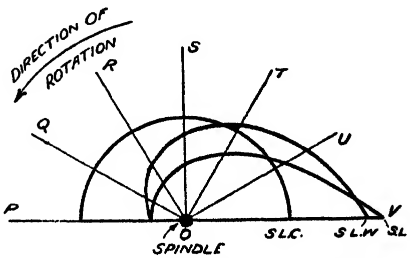


FIG. 6.—THIS SHOWS THE THREE MAIN TYPES OF CONDENSER VANES SUPERIMPOSED FOR EASY COMPARISON.

The Differential Condenser

The DIFFERENTIAL CONDENSER is another type of variable condenser used for reaction control. It consists of two straight line capacity condensers combined into one condenser. (See Fig. 7.) The maximum capacity of the condenser can exist between either the moving vanes and fixed vanes 1, or between the moving vanes and fixed vanes 2, and *in all positions* the total capacity is approximately the same, and equal to the maximum capacity.. As the capacity is increased on one side it is decreased on the other side at the same rate. Thus the capacity of this condenser is only variable in as far as the distribution of the capacity between the two sides is concerned, the total capacity remaining constant. This device enables a small defect in reaction circuits to be remedied, and we shall deal with this later.

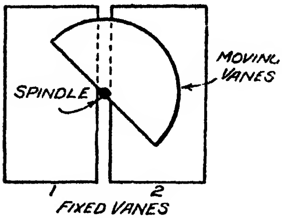


FIG 7.—PLAN OF VANES OF A DIFFERENTIAL CONDENSER

How to Determine the Capacity of a Condenser

Now the capacity of a condenser can be calculated, and depends on such factors as the area of overlap of the two sets of vanes, the number of vanes, the distance between them, and so on. Capacity is measured in microfarads (abbreviated as mfd.), and micro-microfarads (m.mfd.). A microfarad is $\frac{1}{1000000}$th part of a farad, which is the unit of capacity, and a micro-microfarad is $\frac{1}{1000000}$th part of a microfarad. Expressing these relations in the forms of equations, we have :—

$$10^6 \text{ mfd.} = 1 \text{ farad, and}$$

$$10^6 \text{ mmfd.} = 1 \text{ mfd.}$$

The usual size of variable condensers ranges from about 0·001 mfd. to about 0·000005 mfd., i.e. from 1,000 mmfd. to 5 mmfd. A condenser of a size larger than 10 or 20 mfd. is very rarely met, and would be unwieldy in its physical dimensions, except in the case of a certain type of condenser known as an ELECTROLYTIC condenser, of which type a size of 1,000 or 2,000 mfd. is frequently used.

The formula for determining the capacity of a condenser is :—

Capacity = $1{\cdot}111 \times 10^{-6} \times$ (the number of spaces between

the two sets of vanes) × (the area of overlap) ÷ (4π × the distance between the vanes)—

i.e. $C = 1{\cdot}111 \times 10^{-6} \times n \times A \div (4\pi d)$ microfarads,

$$i.e.\ C = 1{\cdot}111 \times 10^{-6} \times \frac{nA}{4\pi d} \text{ mfd.} \qquad (1)$$

$$\text{or } C = 8{\cdot}85 \times 10^{-8} \times \frac{nA}{d} \text{ mfd.} \qquad (1\text{A})$$

In the formula all the measurements are in the metric system —*i.e.* the area A is measured in square centimetres and the distance d in centimetres. Equations (1) and (1A) only apply to the particular case of a condenser with an air gap between the two sets of vanes.

Specific Inductive Capacity

When some other material is used, such as Bakelite or mica, the formula becomes :—

$$C = 1{\cdot}111 \times 10^{-6} \times \frac{nkA}{4\pi d} \text{ mfd.} \qquad (2)$$

$$\text{or } C = 8{\cdot}85 \times 10^{-8} \times \frac{nkA}{d} \text{ mfd.} \qquad (2\text{A})$$

where k is a number which depends on the particular insulating material used between the vanes. The material is called a DIELECTRIC material, and the number k is its SPECIFIC INDUCTIVE CAPACITY or S.I.C.

Material.	S.I.C. (k).
Air	1·0
Ebonite	2·0 to 2·5
Flint glass	7·0 to 10·0
Gutta percha	2·5
Insulating oil	2·0 to 3·0
Mica	5·0
Paper	1·8 to 2·5
Paraffin (solid)	2·0
Plate glass	6·0 to 8·0
Porcelain	4·0 to 6·0
Resin	1·7
Shellac	3·0 to 3·5
Sulphur	2·6
Turpentine	2·1 to 2·3

The table gives the value of k for different substances which are commonly employed as dielectrics. It will be seen that, for air, $k = 1$, and putting this value for k in equation (2) we obtain equation (1), which is the special case for air dielectric. The number k is actually the ratio of the capacity of a condenser when the dielectric material is employed to the capacity when the material is removed and the dielectric is air. Thus we see that if we take a variable condenser with air dielectric and capacity of 0·0005 mfd. and employ sheets of solid paraffin wax as dielectric, the capacity will be increased to $0{\cdot}0005 \times 2{\cdot}0$, *i.e.* to 0·001 mfd. Where a range of values is given for k in the above table, the actual value depends on the quality and purity of the material employed.

To Determine Condenser Capacity

In order to find the capacity of a condenser by means of the formulæ in equations (1) and (2), we need to know the area of overlap of the two sets of vanes. In the case of square law, straight line frequency, and log law types, it is not easy to calculate the area of the vanes. In most cases the maximum capacity of a condenser is marked on one of its end-plates, but there are occasions when it is necessary to know the maximum capacity of a condenser which is not so marked. To do this all that is needed is a sheet of graph paper marked in squares of side 1 cm.

Each big square, of area 1 sq. cm., will probably be divided into twenty-five small squares, each of area $\frac{1}{25}$th sq. cm. Cut out a piece of paper the *exact* shape of one of the moving vanes. In most cases the portion of the moving vane near to the spindle does not overlap the fixed vanes, hence cut out a shape around the spindle so that the final shape of the paper (see Fig. 8) is the exact shape of the area of the moving vanes which overlaps in the maximum capacity position. Count the number of *complete* small squares on the paper, and also the number of fractions of a small square, whether they are smaller or larger than a half square. Divide the latter number by two, and add the result to the former number. Divide the new number by twenty-five, and the result is approximately the area of overlap (A) in square centimetres required for the formula—

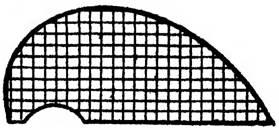


Fig. 8.—Showing how the Capacity of a Condenser can be Calculated

i.e. if S = the number of complete small squares, and
F = the number of fractions of a small square,

$$\text{then Area} = \left(S + \frac{F}{2}\right) \div 25 \text{ sq. cm.}$$

Note.—If there are 100 small squares in each square centimetre, the area is obtained by dividing by 100, and not by twenty-five.

DESIGN OF VARIABLE CONDENSERS

The extremely wide range of variable condensers on the market makes the choice of any particular instrument rather difficult. But as the condenser will, in nearly every instance, have not a little influence on the efficiency and ease of operation of the set in which it will be used, it is well to consider in some detail the available types.

Most variable condensers have an air dielectric, but there are a few in which the dielectric consists of mica, Bakelite or other insulating material. The former are always more efficient because air is the most perfect dielectric material known, causing the very minimum waste of energy. On the other hand, the solid dielectrics, although having lower efficiencies, have what is known as a higher "dielectric constant," which means that a smaller area of electrodes (vanes) is required to make a condenser of any given capacity. In addition, the vanes can be placed much nearer together without there being the least fear of causing a short circuit. And the nearer together the vanes are placed the greater the capacity for any particular electrode area. In consequence, the physical size of a condenser with solid dielectric is enormously less than that of an air dielectric condenser of equal capacity. Another disadvantage of solid dielectric condensers is that their "all out," or minimum capacity, is comparatively high; this point will come up for consideration later on.

It will be clear from the above brief explanation that, generally speaking, it is unwise to employ a solid dielectric variable condenser for the tuning circuit of any set in which a high degree of sensitivity is required. Such a condenser is nevertheless very useful for tuning a set of the portable type where space and weight are important considerations, and where maximum efficiency is frequently a matter of compromise.

A solid dielectric condenser is also very useful for reaction control for, being virtually in shunt with the high-tension voltage, insulation is a matter of great importance. Besides, condenser efficiency is of little consequence in this part of the circuit, because any loss can be restored by increasing the strength of reaction coupling; this means that a slightly higher condenser setting will be required to produce oscillation. A low minimum capacity is not necessary in a reaction condenser because a certain amount of capacity is always required to be in circuit.

Desirable Features

The efficiency of a variable condenser depends not only upon the dielectric material, but also on a number of other features. There are so many important constructional details that it is difficult to arrange them in order of importance, but perhaps one should first mention mechanical rigidity. A rigid structure is very desirable, because there is then less fear of the moving and fixed vanes touching. In addition to this, however, a condenser of flimsy build is always troublesome, because it is impossible to calibrate it with any degree of accuracy.

A sound method of mounting the spindle is the next consideration, and here a cone and ball bearing is generally preferable to all other methods. Some tensioning device for regulating the friction between the spindle and framework is also desirable for this makes it possible to compensate for any wear which might take place, and enables one to regulate the stiffness to suit personal requirements.

The method of making connection between the moving vanes and corresponding terminal is important, and provided it is of suitable material, a "pigtail" undoubtedly gives the most reliable contact. The pigtail should consist of either braided wire or a flat spring, to ensure that no breakage can occur.

Electrical Requirements

The principal requirement from the electrical point of view is that all solid dielectric should be avoided so far as possible. A certain amount *must* be used to insulate the spindle, but this should be kept outside the electro-static field. To fulfil this requirement it is necessary to dispense with a lower-spindle mounting bush; this makes it doubly essential to use a really sound mounting at the upper end.

Some dual gang condensers have two drum dials, which can be operated together to give normal ganged tuning, or separately when either section requires to be trimmed. This type of drive is useful when the two condenser sections are used to tune two unmatched circuits, such as, for instance, a frame aerial and a tuned grid-coil.

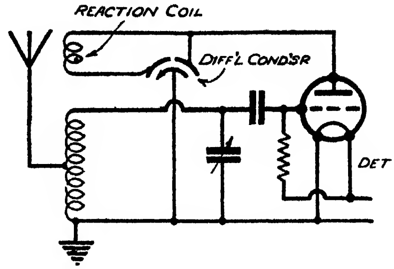


FIG. 10.—CONNECTION TO A DIFFERENTIAL REACTION CONDENSER.

There are also straight-line dials, and when the knob is rotated the pointer moves over a horizontal scale. This type of dial is very popular, principally due to the fact that it can be read very easily and station names can be included.

Differential Condensers

Differential condensers are similar to ordinary variable condensers except that they have two sets of fixed vanes, and consequently three terminals. The moving vanes, which are connected to the centre terminal, can be put into mesh with either set of fixed ones, and are in fact generally partly in mesh with both.

Differential condensers are always of the straight-line capacity type, so that the sum of the capacities between the moving and both sets of fixed vanes remains constant and the capacity of the moving to each set of fixed vanes is proportional to the dial reading.

These condensers are generally employed for reaction purposes, to keep the detector anode-earth capacity constant. This removes the probability of tuning being upset by reaction adjustments. The usual method of connecting a differential reaction condenser is shown in Fig. 10.

Connecting Moving Vanes to Earth

In using all types of variable condensers the moving vanes should be connected to earth. It removes the difficulty of "hand-capacity" due to touching the operating knob and, also, if a metal panel were used it would be earth-connected and the moving vanes would be in contact with the panel.

FIXED CONDENSERS

The fixed condensers used in radio work almost invariably employ some form of solid dielectric so that the capacity of the condenser can be as large as possible for a given physical size. The spacing between vanes is also extremely small, being of the order of a few thousandths of an inch. (*Note.*—The engineer uses the term MIL in referring to small distances of this order. 1 mil = $\frac{1}{1000}$ inch. Thus the distance between the plates of a fixed condenser is of the order of a few mils only.) Calculating the capacity of fixed condensers is seldom necessary, as it is impossible to measure area of overlap, the distance between plates, and so on, without first ruining the condenser by taking it to pieces. The more important features of a fixed condenser are :—

(1) It must be highly efficient, particularly when used in the input, or radio-frequency, stages of a receiver.

(2) It must withstand the voltages applied to it without breaking down, and thus causing a short circuit.

(3) Its capacity must remain constant during operation under all normal working conditions.

Generally speaking, copper foil and mica dielectric type condensers are the most efficient of the solid dielectric fixed condensers, but this type is not available in sizes larger than about 0·1 mfd. due to increased production costs for larger sizes. For capacities bigger than this the condenser is usually made of metal foil and waxed paper dielectric, these materials being in strips and wound together. The condenser is thus built up in a roll which can be compressed into a small space. In this type, sizes up to 8 mfd. are quite common. The electrolytic condenser consists of a metal plate in a chemical solution. The second electrode, or plate, is the metal container holding the solution. These condensers are only for use in D.C. circuits, and are available up to about 2,000 mfd.

CHAPTER X

INDUCTANCE AND TUNING

TUNING coils and chokes can be obtained in a wide variety of shapes and sizes. Some coils are wound in several layers and others in a single layer; some chokes have a great amount of iron used in their construction, and others are simply large multi-layer coils wound in several sections and without iron. They all have one thing in common, however, something possessed by every piece of wire, whether straight, curved, or bent into any other configuration; whether two inches or two miles long. That something goes by the name INDUCTANCE.

Dynamic Fields.

In the earlier chapters we have shown that when an alternating current is passed through a wire the magnetic field which is created around the wire is a variable, or DYNAMIC, field and not a fixed, or STATIC, field. The field grows as the current strength rises from zero to a maximum, and when the current reaches its maximum value the field is also at a maximum. As the current decreases to zero and reverses so the field decreases and commences to grow again in the opposite direction, giving a reversed field corresponding to the negative half-cycle of the current wave. The whole process is exactly similar to the periodic variation of alternating currents and voltages which we have already considered.

Induction

Suppose that we take two wires, say P and S, placed parallel and adjacent to each other without actually touching, and arrange them so that the ends of P are connected to a source of alternating current, and the ends of S to a voltmeter which indicates alternating voltages. We shall find that an alternating voltage exists across the ends of the wire S, although apparently no current is

passing through it since it is not connected to the alternating current source. If we move S so that it is closer to P and still parallel to it the voltage indicated by the voltmeter is increased, and when we increase the distance between the two wires the voltage reading is decreased. This effect is known as INDUCTION, and it is due to the wire S being placed in the variable magnetic field around the wire P. The more intense the part of the field in which S is placed, the greater is the induction effect, and *vice versa*.

Only a Dynamic Field causes Induction

If we connect the ends of P to a battery, or to any direct current supply, instead of to the alternating current source, no voltage is indicated by the voltmeter when the current is switched on. We should notice a slight flick of the voltmeter needle as we switched on, but not a constant reading. The induction occurs only when the field linking the two wires is a variable, or dynamic, field. This accounts for the slight flick of the needle just as the current is switched on, for at that instant the field around P is growing from zero (no current passing) to its steady value (the static field due to the direct current). This growth is momentary and causes momentary induction.

The Effect of Induction in a Coil

From the word "induction" we have derived our term "inductance." Thus we see that inductance has to do with an effect which occurs when a wire is placed in the dynamic magnetic field around a second wire. When we have a coil consisting of several turns of wire and carrying an alternating current, the current in each turn of the wire creates a magnetic field which induces a voltage in every turn of wire in the coil. The more turns of wire on a coil, the greater the induction effect. The induced voltages can be added together and the mathematician has a formula which tells him the voltage across a coil due to an alternating current in the coil. The effect of induction is to cause a coil to offer greater resistance to alternating currents than to direct currents, and this is dealt with later in this chapter. In order to distinguish between the induction effect which occurs when two coils are placed near to each other from the induction between the turns of a single

coil, the former effect is called MUTUAL INDUCTION and the latter SELF-INDUCTION.

Calculating Inductance

We are able to calculate how great is the induction effect of a coil, and the calculation depends on the knowledge of such factor as the shape of the coil, its size, the gauge wire used in its construction, and so on. The induct*ance* of a coil is the mathematician's measure of the extent of the induct*ion* effect. Inductance is measured in " henries " and in sub-multiples of a henry, viz., millhenries and microhenries, the millihenry being $\frac{1}{1000}$ th of a henry, and the microhenry $\frac{1}{1000000}$ th of a henry. Expressing these relations in the form of equations, we have :

10^3 millihenries = 1 henry,

10^6 microhenries = 1 henry, and hence

10^3 microhenries = 1 millihenry.

Formulæ relating to Coil Inductance

Our choice of formula must depend to a great extent on what type of coil we are considering. Special formulæ have had to be invented for dealing with multi-layer and unusual shaped coils. Let us consider the simple case of a single layer coil wound on a cylindrical former. Such a coil is usually termed a " solenoid." The radius of the cylinder, the length of the winding and all other measurements must be made in centimetres and not inches, and all measurements in inches must be converted into centimetres. Fig. 1 shows a diagram of the simple coil we are considering. The diameter is d centimetres, the total length of the winding is l centimetres, and N is the total number of turns on the coil. Then :—

Inductance = $9{\cdot}87 \times 10^{-3} \times (\text{diam.})^2 \times (\text{No. of turns})^2 \times$ (a certain number, called K) $\div$ (length),

i.e., $$L = 9{\cdot}87 \times 10^{-3} \times d^2 \times N^2 \times K \div l,$$

or $$L = 9{\cdot}87 \times 10^{-3} \times \frac{d^2N^2}{l} K \text{ microhenries} \quad \ldots \quad (1)$$

The letter "L" is the mathematical symbol for inductance, and the number K depends on the ratio of the diameter of the coil to the length of the winding, viz., $\frac{d}{l}$. The accompanying table shows the value of K for different values of $\frac{d}{l}$.

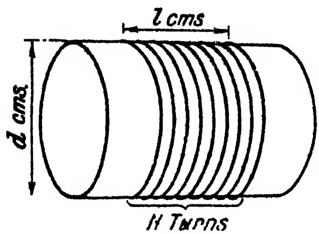


FIG. 1.—A SIMPLE SINGLE LAYER COIL WOUND ON A CYLINDRICAL FORMER.

As an example of the use of the formula of equation (1), suppose that we wish to find the inductance of a coil of 100 turns of wire on a 2½-inch diameter former, the length of the winding being 1½ inches. Firstly, we must convert these measurements to centimetres, which we can do if we remember that 1 inch = 2·5 centimetres (approximately). Hence:—

2½ inches = 6·25 centimetres.

1½ " = 3·75 "

Therefore, d = 6·25 "

l = 3·75 "

N = 100

$$\frac{d}{l} = \frac{625}{375} = \frac{25}{15} = \frac{5}{3} = 1{\cdot}7 \text{ approx.}$$

The value of $\frac{d}{l}$ is actually 1·66 . . ., the figure 6 recurring, but our answer will be sufficiently accurate if we take this to the nearest first decimal place, viz., 1·7. From the table we see that the value of K corresponding to $\frac{d}{l}$ = 1·7, is K = 0·56.

Therefore we have:—

$$L = 9{\cdot}87 \times 10^{-3} \times \frac{6{\cdot}25 \times 6{\cdot}25 \times 100 \times 100}{3{\cdot}75} \times 0{\cdot}56 \text{ microhenries,}$$

and working out the arithmetic, we find that

L = 576 microhenries (approximately).

$\frac{d}{l}$	K	$\frac{d}{l}$	K
0·0	1·0	1·4	0·61
0·1	0·96	1·5	0·60
0·2	0·92	1·6	0·58
0·3	0·88	1·7	0·56
0·4	0·85	1·8	0·55
0·5	0·82	1·9	0·54
0·6	0·79	2·0	0·53
0·7	0·76	5·0	0·32
0·8	0·74	10·0	0·20
0·9	0·71	20·0	0·12
1·0	0·69	30·0	0·09
1·1	0·67	40·0	0·07
1·2	0·65	50·0	0·06
1·3	0·63	100·0	0·03

Induction in Wireless Circuits

The effect of induction is highly important in wireless circuits; in fact, were it not for induction we should be unable to tune a circuit so as to receive signals of different wavelengths. In a tuning circuit the greater the inductance used the longer the wavelength to which the circuit tunes. Most modern receivers cover three wavebands—called the short, medium and long wavebands—and a switch is provided for effecting the change over from one waveband to the other.

Inductance between Two Coils

Fig. 2 shows two coils joined together in series. Coil AB has an inductance of L_1 microhenries (mH) and BC of L_2 mH. The switch S short circuits BC when closed, and the inductance in circuit is L_1. When S is open, the inductance is the total effect of L_1 and L_2 joined in series. If the two coils are some

distance apart, or screened from each other, then the total inductance (L) is obtained by adding L_1 and L_2 together, thus :—

$$L = L_1 + L_2 \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

If the two coils are close to each other, as they would be if wound on the same former, each will be within the dynamic field of the other, and hence the separate induction effects of each are enhanced by interaction. The interaction between two coils is what we have already termed mutual induction. It is measured as so much inductance, just as is the self-induction effect of a single coil.

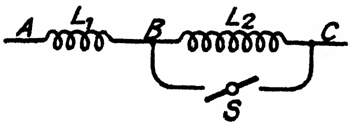


FIG 2.—TWO COILS JOINED TOGETHER IN SERIES.

Mutual Inductance

The letter M is used as a symbol for mutual inductance in mathematical shorthand. Thus, in the circuit of Fig. 3, if AB and BC mutually affect each other, so that their mutual inductance is M microhenries, the total inductance (L) in the circuit is obtained by adding up the enhanced inductances of each coil, thus :—

$$L = (L_1 + M) + (L_2 + M)$$
$$\text{or } L = L_1 + L_2 + 2M \quad \ldots\ldots\ldots \quad (3)$$

If we take two coils which are wound in opposite directions, as in Fig. 4, and place them together as shown and connect the ends B and C, the mutual induction effect will detract from the self-induction effects of each coil. Thus we have :—

$$L = (L_1 - M) + (L_2 - M)$$
$$\text{or } L = L_1 + L_2 - 2M \quad \ldots\ldots\ldots\ldots \quad (4)$$

Two coils placed together and connected in this way are said to be negatively coupled.

TUNED CIRCUIT CALCULATIONS

In Chapter VI, when dealing with resistance, it was shown that Ohm's Law can be stated in the form of an equation, thus :

$$E = IR \quad \ldots\ldots\ldots \quad (1)$$

i.e., the voltage (E) produced across the ends of a wire, of resistance R, carrying a current I is equal to the product of I and R.

In this case the current is a direct current and the voltage a steady, or direct, voltage. It is immaterial whether we think of the current as producing the voltage or of the voltage as producing the current; both are different aspects of the one event.

FIG. 3.—DIAGRAM SHOWING MUTUAL INDUCTANCE.

A.C. Circuit Calculations

If we connect a resistance in the circuit of an alternator so that an alternating voltage is applied across its ends, an alternating current will pass through the resistance. Provided that the circuit contains neither inductance nor capacity, the same relation exists between the voltage and current as exists in the case of the D.C. circuit, viz. :—

$$E = IR_{A.C.} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The suffix after the R denotes that the equation refers to an A.C. circuit. In this case, E and I are either R.M.S. or peak values. It is immaterial which, provided that they are both the same. This is easily shown, for we have :—

$$E = \frac{E_0}{\sqrt{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$\text{and } I = \frac{I_0}{\sqrt{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

In (2) put in the values (3) and (4) for E and I, then :—

$$\frac{E_0}{\sqrt{2}} = \frac{I_0 R_{A.C.}}{\sqrt{2}}$$

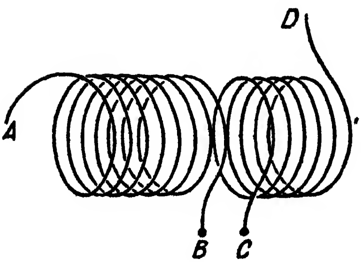


FIG. 4.—MUTUAL INDUCTION BETWEEN COILS WOUND IN OPPOSITE DIRECTIONS.

Cancelling the $\sqrt{2}$ from each denominator we have :—

$$E_0 = I_0 R_{A.C.},$$

which is an equation of the same type as (2) with peak values for voltage and current in place of R.M.S. values.

Now the resistance, $R_{A.C.}$, which the wire offers to the output from the alternator is not the same as the resistance which it

offers in a D.C. circuit. The A.C. resistance of a wire is greater than its D.C. resistance, but in the case of alternating currents of power frequencies the increase from $R_{D.C.}$, to $R_{A.C.}$ is very small, and for almost all practical purposes the A.C. resistance can be taken to be the same as the D.C. resistance.

Resistance at Radio Frequencies

In the case of frequencies greater than 2,000 or 3,000 cycles per second, the increase in resistance is measurable, and the A.C. resistance is very often several times its D.C. counterpart. As an example, consider the case of a 250 mH coil with a D.C. resistance of the order of 1·5 ohms. When tuned to 600 metres with a 0·0005 mfd. condenser, the A.C. resistance (of the coil only) to a signal of this wavelength-frequency = 500 kc/s.—would be of the order of 4·0 ohms. It is important to note that we are here considering the actual resistance of the coil quite apart from any effects of resistance due to its inductance or to the capacity used for tuning.

Skin Effect

The increase in resistance with frequency is due to what is known as a "skin" effect. In the case of a wire carrying direct current, the current is equally distributed over the whole of the cross-section of the wire. In an A.C. circuit, the current is forced to travel on the surface of the wire (see Fig. 5). The greater the frequency of the current, the more pronounced the effect becomes—i.e., the nearer to the surface the current is forced to travel. The extent of the effect varies with the material of which the wire is made and with the shape of the wire. In the case of a straight length of copper wire, if we denote the A.C. resistance at radio frequency by $R_{A.C.}$ and the D.C. resistance by $R_{D.C.}$ as previously, we have the following relation between these quantities :—

$$R_{A.C.} = (0{\cdot}097\, d \sqrt{f} + 0{\cdot}25) \times R_{D.C.} \qquad (5)$$

Where d is the diameter of the wire in inches and f is the frequency of the current in cycles per second.

Calculating A.C. Resistance

Thus we see that if we know the D.C. resistance of a wire, its diameter and the frequency of the current (or voltage), we can calculate the A.C. resistance. As an example, let us find the value of $R_{A.C.}$ when $R_{D.C.} = 2{\cdot}5$ ohms, $d = 0{\cdot}012$ inches, and the frequency is 1,000 kc/s. We have :—

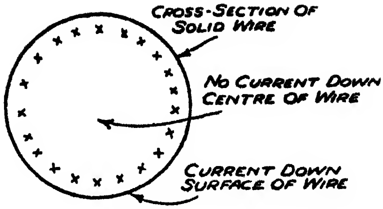


FIG. 5.—SHOWING HOW CURRENT TRAVELS ON THE SURFACE OF A WIRE IN AN A.C. CIRCUIT.

$R_{A.C.} = (0{\cdot}097 \times 0{\cdot}012 \times \sqrt{1{,}000{,}000} + 0{\cdot}25) \times 2{\cdot}5$ ohms.

i.e., $R_{A.C.} = (0{\cdot}097 \times 0{\cdot}012 \times 1{,}000 + 0{\cdot}25) \times 2{\cdot}5$ ohms.

i.e., $R_{A.C.} = 3{\cdot}5$ ohms (approx.).

This formula is only applicable to radio-frequency calculations, and must not be applied to cases of audio and power frequencies.

The resistance with which we have been dealing is often referred to as pure resistance to emphasize the fact that it has no connection with the resistance effects due to the inductance and capacity of a circuit.

Steinmetz's Law

Professor Ohm discovered the law showing the relation between the current, voltage, and pure resistance of a circuit. Steinmetz discovered a law, which has been called the Extension of Ohm's Law, and which states the relation between the current, voltage, and the EFFECTIVE RESISTANCE of any circuit. The term IMPEDANCE is frequently used in place of effective resistance. The law is :—

$$E = IZ \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where Z is the impedance of the circuit. Put in words, the equation states : " The voltage E produced across the ends of a circuit of impedance Z and carrying an alternating current I is equal to the product of I and Z." When E is measured in volts and I in amperes, the impedance Z is measured in ohms. E and I may be either R.M.S. or peak values, provided that they are both the same.

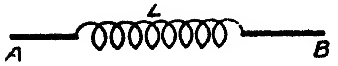


FIG. 6.—A CIRCUIT COMPRISING A COIL OF INDUCTANCE L HENRIES.

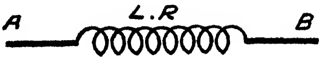


FIG. 7.—CIRCUIT COMPRISING A COIL OF RESISTANCE R OHMS AND INDUCTANCE L HENRIES.

The Impedance of a Circuit

The impedance of a circuit is the resistance which results from the presence of some combination of inductance (L), capacity (C), and resistance (R) in the circuit, and there are, in all, seven ways of combining them, viz. :—

L only,
C only,
R only (Ohm's Law itself),
L and C,
C and R,
R and L,
L, C and R.

In each case there is an infinite number of ways in which the inductance, capacity and resistance may be connected. Thus, in the case of inductance only there may be one, two, three, and so on, inductances, all of different inductance value, connected in series, parallel, or in any series-parallel combination. The same applies to the more complex arrangements. We shall consider only the simpler cases frequently encountered in radio circuits.

In actual practice, every length of wire and every coil possess both pure resistance and pure inductance. In a great many cases, however, the effect of either resistance or inductance is so great as to swamp the effect of the other. A pure inductance is the term applied to a coil of which the resistance is negligible. In the case of condensers, every condenser behaves in a circuit as though it comprises both pure capacity and pure resistance, but the effect of the resistance component is generally small and will be neglected for the present.

The impedance of a circuit consists of two parts: (1) the pure resistance, and (2) the REACTANCE. The latter is the effect of the pure inductance and the pure capacity of the circuit apart from the pure resistance. In simple circuits the reactance depends on the value of the inductance, the capacity, and the

frequency of the current in the circuit. In considering the simple cases of impedance, we shall express the results in the form of equations and we shall employ X and Z as a shorthand notation for reactance and impedance respectively. We shall find that the term $2\pi f$ occurs very frequently throughout all impedance calculations and the mathematician saves time by writing the Greek letter "ω," pronounced "omega," as shorthand for $2\pi f$. That is, he makes the substitution $\omega = 2\pi f$, and wherever he sees $2\pi f$ he writes ω.

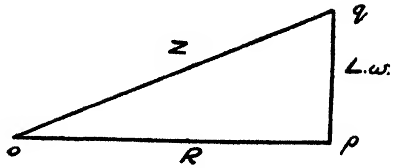


FIG. 8.—RIGHT-ANGLED TRIANGLE WHOSE SIDES REPRESENT L.ω, R AND Z OF FORMULA (9).

Fig. 6 shows a circuit comprising a coil of inductance L henries. The reactance of the circuit across the terminals A and B is :—

$$X = L \times 2\pi f \text{ ohms} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where f is the frequency of the current and π has the usual value of 3·1416. When L is in henries the reactance is expressed in ohms. There is no pure resistance in the circuit and the impedance is thus equal to the reactance :—

i.e., $Z = X$

$\therefore$ $Z = L \times 2\pi f$ ohms . . . . (8)

Writing ω for $2\pi f$ in (7) and (8) we have :—

$$X = L\omega \text{ ohms} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7a)$$

$$\text{and } Z = L\omega \text{ ohms} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8a)$$

Now suppose that the coil has a resistance of R ohms, as well as inductance L henries (see Fig. 7). As before, the reactance is :—

$$X = L\omega \text{ ohms.}$$

The pure resistance is R ohms, and the impedance is :—

$$Z = \sqrt{R^2 + (L\omega)^2} \text{ ohms} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

An example of this formula is given later.

Note that this equation reminds us of a certain well-known theorem in geometry, viz., Pythagorus' Theorem. If Z were

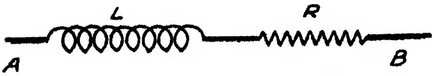


FIG. 9.—A PURE INDUCTANCE OF L HENRIES JOINED IN SERIES WITH A PURE RESISTANCE OF R OHMS.

the length of the hypotenuse of a right-angled triangle and R and $L\omega$ were the other two sides (see Fig. 8), then :—

$$\text{Hypotenuse} = \sqrt{(\text{1st side})^2 + (\text{2nd side})^2} \quad . \quad . \quad . \quad . \quad (10)$$

i.e., $$Z = \sqrt{R^2 + (L\omega)^2}.$$

If we have a pure inductance of L henries joined in series with a pure resistance of R ohms as in Fig. 9, the reactance is :—

$$X = L\omega \text{ ohms,}$$

and the impedance between A and B is :—

$$Z = \sqrt{R^2 + (L\omega)^2 \text{ ohms.}}$$

This equation is the same as (9), *hence we must conclude that the effect is the same as that of a coil and no additional resistance, the coil possessing both the inductance and resistance* (see Fig. 7).

The circuit of Fig. 10 shows a pure capacity C. The reactance of the circuit is :—

$$X = \frac{1}{C\omega} \text{ ohms} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

(NOTE.—The reactance is in ohms if C is in farads.)

There is no pure resistance, hence the impedance equals the reactance :—

i.e., $$X = Z,$$

$$\therefore \quad Z = \frac{1}{C\omega} \text{ ohms} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Coil and Condenser in Series

We will consider one more case, viz., that of a circuit comprising a coil and condenser connected in series, the coil possessing inductance and resistance and the condenser possessing pure capacity only (Fig. 11). In this case we have :—

$$X = L\omega - \frac{1}{C\omega} \text{ ohms} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and

$$Z = \sqrt{R^2 + \left(L\omega - \frac{1}{C\omega}\right)^2} \text{ ohms} \quad . \quad . \quad . \quad (14)$$

Impedance of a Low-frequency Choke

In all these cases we have merely stated the resulting reactance and impedance without proving the statements and without even indicating how the result is obtained. We have neither space nor time here, however, to consider these points and the results must be accepted as established. In illustration of the application of the equations, let us find the impedance of a low-frequency choke of inductance 30 henries and resistance 400 ohms. Since the impedance also depends on the frequency of the alternating current we must state the frequency at which the impedance is required. Let us find it for frequencies of 50 and 400 cycles per second.

Case 1.—($f = 50$).

The reactance is :—

$$X = L\omega \text{ ohms.}$$

and writing in the values of L and ω we have :—

$$X = 30 \times 2 \times 3{\cdot}14 \times 50 \text{ ohms,}$$

i.e.,
$$X = 9{,}420 \text{ ohms.}$$

If the choke possessed no resistance its impedance at 50 cycles per second would be the same as its reactance, viz., 9,420 ohms. Putting R = 400 in equation (9), we have :—

$$Z = \sqrt{400^2 + 9{,}420^2} \text{ ohms,}$$

i.e.,
$$Z = \sqrt{88{,}896{,}400} \text{ ohms,}$$

or
$$Z = 9{,}430 \text{ ohms.}$$

That is to say, the effect of the 400 ohms pure resistance is only 0·1 per cent. of the effect of the reactance, or negligible for all practical purposes. We should give the impedance as 9,420 ohms and neglect entirely the effect of the 400 ohms. It is not necessary to work out the somewhat difficult square root in order to discover whether R is small enough in comparison with $L\omega$ to be neglected. Provided that the one term in the square root expression is less than one-fifth of the other the smaller term may always be neglected.

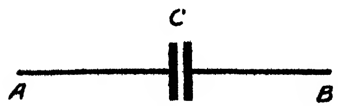


FIG. 10.—CIRCUIT SHOWING A PURE CAPACITY C.

FIG. 11.—CIRCUIT COMPRISING A COIL AND CONDENSER CONNECTED IN SERIES.

Case 2.—(f = 400).
The reactance is :—

$$X = L\omega \text{ ohms.}$$

i.e., $$X = 30 \times 2 \times 3{\cdot}14 \times 400 \text{ ohms.}$$

or $$X = 75{,}360 \text{ ohms.}$$

In this case, the 400 ohms resistance is certainly less than ⅛th of the 75,360 ohms reactance, and hence will be neglected in the final answer. The impedance for a frequency of 400 cycles is thus :—

$$Z = 75{,}360 \text{ ohms.}$$

Impedance of a Condenser

Let us also find the impedance of a condenser of capacity 2 mfd. at frequencies of 50 and 300 cycles per second. From (11) we have :—

Case 1.—(f = 50)

$$Z = \frac{1}{C\omega} \text{ ohms, when C is measured in } \textit{farads,}$$

i.e., $$Z = \frac{1}{C\omega} \times 10^6 \text{ ohms, when C is measured in } \textit{microfarads.}$$

writing in the values of C and ω we have :—

$$Z = \frac{1}{2 \times 2 \times 3{\cdot}14 \times 50} \times 10^6 \text{ ohms,}$$

i.e., $$Z = 1{,}590 \text{ ohms (approx.).}$$

Case 2.—(f = 300)

$$Z = \frac{1}{2 \times 2 \times 3{\cdot}14 \times 300} \times 10^6 \text{ ohms.}$$

i.e., $$Z = 265 \text{ ohms (approx.).}$$

It will be seen from these examples that (1) an increase in frequency causes an increase in impedance in the case of an inductance, and *vice versa,* and (2) an increase in frequency causes a decrease in impedance in the case of a capacity, and *vice versa.* These two facts are highly important in radio design and they explain, for instance, why the efficiency of intervalve couplings varies with the frequency.

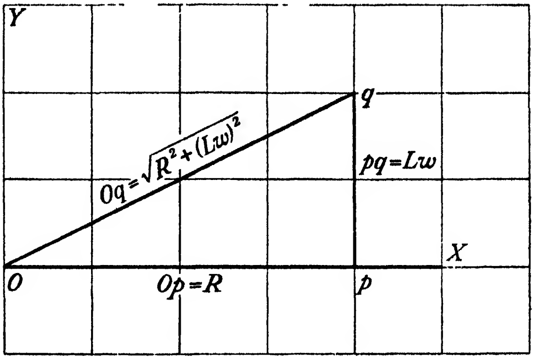


FIG. 12. SHOWING HOW THE IMPEDANCE OF A CIRCUIT CAN BE EXPRESSED BY TRIANGLE.

Vector Representation and Vector Impedance

There is another form in which the impedance of circuits can be expressed. We have already noted that the equations we have obtained are similar in form to the equation expressing the result of Pythagorus' Theorem. Let us take a piece of squared paper and draw two axes, OX and OY, and measure resistance along the OX axis and reactance along the OY axis. In Fig. 12, the triangle O*pq* was obtained by measuring first a length O*p* along OX equal to R ohms, and then a length *pq*, parallel to OY (i.e., perpendicular to OX), equal to Lω. The line O*q* then represents the impedance of the circuits of Figs. 7 and 9. We may write this operation as follows :—

O*q* = result of O*p* (= R) along OX and *pq* (= Lω) upwards and parallel to OY.

Let us use a shorthand notation to abbreviate this statement. We may write :—

$$Oq = (R) \text{ and } (+jL\omega) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

In this equation the letter j denotes that the length Lω is measured in a direction perpendicular to OX, *i.e.*, perpendicular to R, and the + sign indicates that the direction of Lω is upwards. When this form of expressing the impedance is employed a small letter z is used for impedance, and both the brackets and the word " and " are omitted. Thus we have finally :—

$$z = R + jL\omega \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Putting this back into words we have :—

" The impedance of the circuit is represented by the

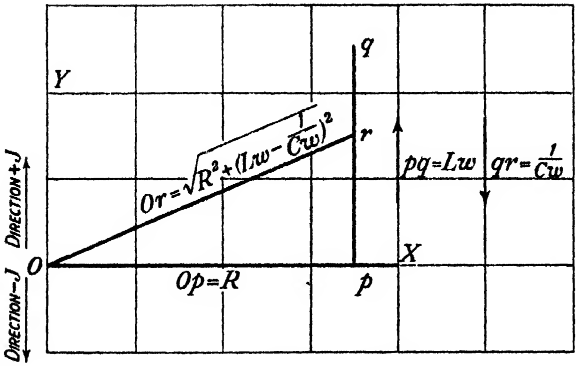


FIG. 13. SHOWING HOW THE IMPEDANCE IS REPRESENTED BY THE HYPOTENUSE OF THE RIGHT-ANGLED TRIANGLE.

hypotenuse of a right-angled triangle of which the other two sides represent the resistance and the reactance respectively."

In the case of the circuit of Fig. 11 we have the following equation as the impedance equation :—

$$z = R + j\left(L\omega - \frac{1}{C\omega}\right) \quad . \quad . \quad . \quad . \quad . \quad (17)$$

This states that the impedance is represented by the hypotenuse of the right-angled triangle which has sides representing R and $(L\omega - \frac{1}{C\omega})$ respectively. The diagram showing this operation is given in Fig. 13. The length Op along OX represents R and the length pr parallel to OY represents the reactance of the circuit. This is split into two parts, the positive part due to the inductance L and equal to $(+L\omega)$, and the negative part due to the capacity C and equal to $(-\frac{1}{C\omega})$. These two parts are shown in the figure by the line pq in the upwards, or $+j$, direction, and the line qr in the downwards, or $-j$, direction.

This representation of the impedance of a circuit is known as the VECTOR REPRESENTATION, and the quantity z is called the VECTOR IMPEDANCE. The vector impedance becomes the actual impedance of the circuit when we draw the right-angled triangle and express the length of the hypotenuse (representing z) in terms of the other sides (representing the reactive and non-reactive components of the circuit).

Tuned Circuits

We have discussed very briefly the impedance of a few of the simpler circuits occurring in radio practice. In particular, we dealt with the circuit comprising an inductance, possessing resistance and joined in series with a capacity as illustrated in Fig. 11. This case is important in radio work, since it is the simplest case of a tuned circuit.

The vector impedance of this circuit is :—

$$z = R + j\left(L\omega - \frac{1}{C\omega}\right),$$

and the line Or in Fig. 13 represents the actual impedance of the circuit. The lines pq and qr represent the positive and negative reactances, respectively, viz., Lω and $\frac{1}{C\omega}$, and pr is the resultant arising from the addition of these two, viz., $\left(L\omega - \frac{1}{C\omega}\right)$. The line O$p$ represents the pure resistance of the circuit, and it is perpendicular to the direction pq. The direction Or is oblique to pq, and measurement of the lines Op and Or will show that Op is the shorter. Whatever the position of r along pq, Op will always be shorter than Or. It is almost intuitive knowledge that the shortest distance from a point to, say, a wall, or a line drawn on the ground, is along the direction which is perpendicular to the wall or line. In this case Op, the perpendicular from O on the line pq, is the shortest line which can be drawn from O to pq. It does not matter whether r is above the OX axis or below it as in Fig. 14, where the negative reactance is greater than the positive reactance, Op is always the shortest distance from O to pq.

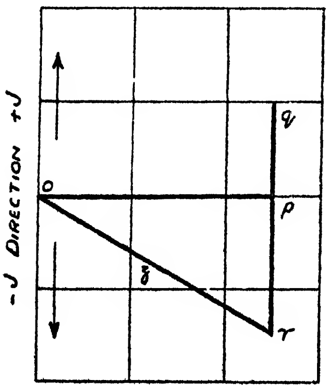


FIG. 14.—SHOWING THAT NO MATTER WHETHER r IS ABOVE THE OX AXIS OR BELOW IT, Op IS ALWAYS THE SHORTEST DISTANCE FROM O TO pq.

Equal Negative and Positive Reactances

Suppose now that the negative reactance is just equal to the positive reactance. The lines *pq* and *qr* will be equal to each other, and the point *r* will coincide with *p*. In this case O*r* is the same as O*p*. That is to say, the impedance—which is represented by O*r*—is also represented by O*p*. But O*p* is the shortest line which can be drawn from O to the direction *pq*, and hence the impedance has its least value when *pq* just balances *qr*. When O*r* is in any other position it is oblique to *pq* and the impedance is greater than the value represented by O*p*. Thus the impedance of the circuit of Fig. 11 has its minimum value when the positive and negative reactances cancel out, *i.e.*, when the total reactance is zero. Expressing this condition in the shorthand notation of an equation we have :—

$$z = \text{minimum value when } L\omega - \frac{1}{C\omega} = O \quad . \quad . \quad . \quad . \quad (18)$$

For all other values of the reactance—*i.e.*, $L\omega$ greater than $\frac{1}{C\omega}$, or *vice versa*—the impedance is greater than this minimum value. We also know the actual value of the minimum impedance. It is represented by O*p*, but O*p* represents the pure resistance of the circuit, and hence the minimum impedance equals the pure resistance of the circuit, thus :—

$$z = R \text{ when } L\omega - \frac{1}{C\omega} = O.$$

Now when the difference of two quantities is equal to zero the two quantities must be equal to each other, hence :—

$$L\omega = \frac{1}{C\omega} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19).$$

This expresses the same fact as (18). It tells us a relation between L, C and ω when the impedance is a minimum. It means nothing when the impedance is not a minimum. Conversely, when this relation exists—*i.e.*, when the inductance, capacity and frequency of the current are such that $L\omega$ and $\frac{1}{C\omega}$ are equal—the impedance is a minimum. Multiply both sides of (19) by $C\omega$:—

$$L\omega \times C\omega = \frac{1}{C\omega} \times C\omega$$

The terms on the right-hand side cancel, leaving :—

$$LC\omega^2 = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

and this is the usual form in which the condition of minimum impedance is usually expressed.

Importance of Minimum Impedance in Radio Design

Suppose that we connect the circuit of Fig. 11, page 241, to a source of signals of various wavelengths or frequencies, such as an aerial. The circuit will offer a certain effective resistance to the signals, but to one particular signal it will offer the least impedance, and this will occur when the frequency of the signal is such that the condition of minimum impedance is satisfied, viz., the condition expressed by (20). This frequency can be calculated if we substitute $2\pi f$ for ω. We have :—

$$LC\,(2\pi f)^2 = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

i.e.,

$$LC\,4\pi^2 f^2 = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21a)$$

and hence minimum impedance is obtained when the frequency is such that when squared and multiplied by ($LC4\pi^2$) the answer is 1.

In (21a) the frequency is in cycles per second when L is in henries and C is in farads. We can express this in a form more convenient for calculating f when L and C are known. Dividing each side by $LC\,4\pi^2$, we have :—

$$LC\,4\pi^2 f^2 \div LC\,4\pi^2 = 1 \div LC\,4\pi^2,$$

i.e.,

$$f^2 = \frac{1}{LC\,4\pi^2}.$$

Taking the square root :—

$$f = \sqrt{\frac{1}{LC\,4\pi^2}},$$

which may be written as :—

$$f = \frac{1}{\sqrt{LC\,4\pi^2}}$$

Now $\sqrt{LC\,4\pi^2} = \sqrt{LC} \times \sqrt{4\pi^2}$,

i.e.,

$$\sqrt{LC\,4\pi^2} = \sqrt{LC} \times 2\pi.$$

Hence

$$f = \frac{1}{2\pi\sqrt{LC}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

As already explained it is usual in wireless circuits to express the inductance in microhenries (mH.) and the capacity in microfarads (mfd.). Hence if L and C be measured in these units we must convert them into henries (H.) and farads (F.) respectively.

i.e., $$\text{L mH.} = \frac{\text{L}}{10^6}\text{ H.}$$

and $$\text{C mfd.} = \frac{\text{C}}{10^6}\text{ F.}$$

Hence, writing these values in (22), we have :—

$$f = \frac{1}{2\pi\sqrt{\frac{\text{L}}{10^6} \times \frac{\text{C}}{10^6}}},$$

i.e., $$f = \frac{1}{2\pi\frac{\sqrt{\text{L} \times \text{C}}}{\sqrt{10^6 \times 10^6}}},$$

i.e., $$f = \frac{1}{2\pi\frac{\sqrt{\text{LC}}}{10^6}}.$$

or $$f = \frac{10^6}{2\pi\sqrt{\text{LC}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

where L and C are now in microhenries and microfarads, and f is in cycles per second. Equation (23) expresses the same condition as (18), but in a more convenient form for calculation. In illustration of the use of (23), consider the case of a circuit in which L = 250 mH., and C = 0·0004 mfd., we have :—

$$\text{LC} = 250 \times 0{\cdot}0004$$

i.e., $$\text{LC} = 0{\cdot}1$$

Thus the circuit offers minimum impedance to a frequency :—

$$f = \frac{10^6}{2\pi\sqrt{0{\cdot}1}} \text{ cycles per second,}$$

i.e., $$f = \frac{10^6}{2 \times 3{\cdot}1416 \times 0{\cdot}3165} \text{ cycles per second,}$$

i.e., f = 503,500 cycles per second (approx.)

or f = 503·5 kc/s.

That is to say, a coil of 250 mH. inductance and a capacity of 0·0004 mfd., joined in series will offer minimum impedance to a signal of frequency 503·5 kc/s., and this minimum impedance is equal to the pure resistance of the coil. This frequency corresponds to a wavelength of 596 metres (approx.). To signals of all other frequencies or wavelengths the impedance will be much greater than the pure resistance of the coil.

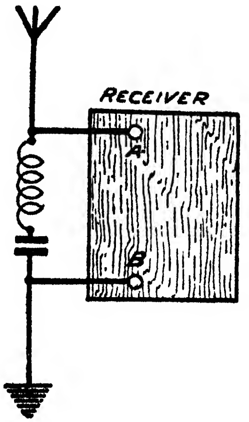


Fig. 15.
Showing Series Circuit Connected in Parallel with Aerial and Earth Terminals of a Set, to Form a Wavetrap.

An immediate application of this circuit is as a wavetrap. Suppose that we connect it in *parallel* with the aerial and earth terminals of a receiver, as in Fig. 15, and suppose that the values of L and C are such that the circuit offers minimum impedance to signals of the same frequency as that of the local station. This is easily arranged by employing a variable condenser and adjusting it until this condition obtains. Then, since electrical signals always tend to travel along the path of least resistance, the local station signals will be passed through the wavetrap, since the path from A to E inside the receiver is of much greater impedance than that of the wavetrap. The impedance of the wavetrap will be greater for signals of other wavelengths, and hence these will operate the receiver in the usual manner. If the wavetrap coil is carefully designed so that its pure resistance is practically nil, then the wavetrap will act almost as a short-circuit to the local station signals.

Resonant Frequency

As we adjust the capacity of the condenser C we are actually adjusting the circuit so that it offers minimum impedance to the local station signals. This process is known by the familiar name of "tuning." The frequency for minimum impedance is often called the RESONANT FREQUENCY, and the whole operation of tuning the circuit so that $L\omega = \frac{1}{C\omega}$ is known as tuning to

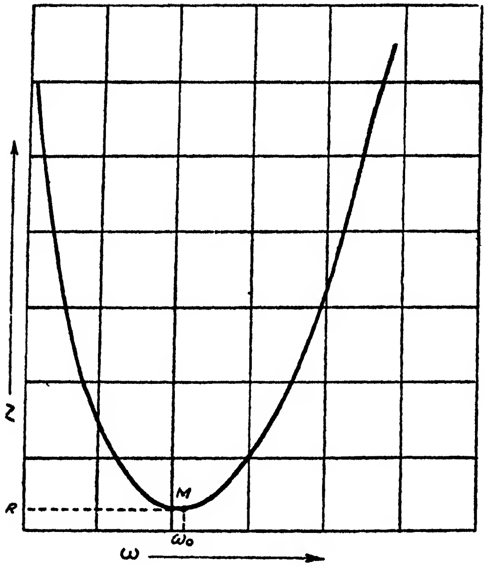


FIG. 16.—GRAPH SHOWING IMPEDANCE AT VARIOUS FREQUENCIES.

Only the general shape of the curve is indicated. The arrows show the direction in which the impedance and the angular frequency increase.

RESONANCE, or causing the circuit to RESONATE, with the particular frequency f.

(NOTE.—f is the frequency of the signal, and ω is called the ANGULAR FREQUENCY.)

Impedance at Various Frequencies

The shape of the graph showing the impedance at various frequencies is shown in Fig. 16. Note that in this case we are not concerned with an exact curve, but only with the general shape of the curve, and hence no numerical values are marked along the axes. The arrows show the directions in which Z and ω increase. We see from this that a minimum value of Z is reached at the point marked M, and the impedance increases rapidly when the frequency is only slightly different from the resonance value, marked ω_0, corresponding to M. Thus, whenever we write ω_0 we know that its value is such that :—

$$L\omega_0 = \frac{1}{C\omega_0}.$$

Frequency in Terms of Wavelength

We can express the frequency of a signal in terms of its wavelength λ, thus :—

$$f = \frac{V}{\lambda}$$

where $V = 300 \times 10^6$, and is the value of the velocity of wireless waves in metres per second. Writing this value for f in (23) we have :—

$$\frac{V}{\lambda} = \frac{10^6}{2\pi\sqrt{LC}}$$

i.e.,
$$\frac{300 \times 10^6}{\lambda} = \frac{10^6}{2\pi\sqrt{LC}}.$$

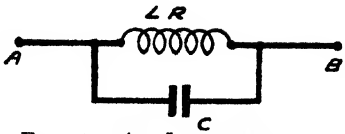


FIG. 17.—AN INDUCTANCE IN PARALLEL WITH A CAPACITY.

cancelling the 10^6 from each side, and inverting both sides we have :—

$$\frac{\lambda}{300} = \frac{2\pi\sqrt{LC}}{1}$$

i.e.,
$$\lambda = 300 \times 2\pi\sqrt{LC}$$

writing 3·1416 for π, and then replacing $300 \times 2\pi$ by 1,885, we have finally :—

$$\lambda = 1{,}885\sqrt{LC} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

This is the well-known formula giving the wavelength to which a circuit resonates in terms of the inductance and capacity. As in (23), L and C are in microhenries and microfarads respectively.

As an example, consider the case of an inductance of 3,000 mH. and a capacity of ·0003 mfd., we have :—

$$LC = 3{,}000 \times 0{\cdot}0003$$

i.e.,
$$LC = 0{\cdot}9$$

Thus the circuit offers minimum impedance to signals whose wavelength (λ) is :—

$$\lambda = 1885 \times \sqrt{0{\cdot}9} \text{ metres}$$

i.e.,
$$\lambda = 1885 \times 0{\cdot}95 \text{ metres}$$
$$\lambda = 1{,}790 \text{ metres.}$$

Inductance in Parallel with a Capacity

This resonance condition also applies to another form of tuned circuit, widely used in radio practice, viz., the parallel circuit in which an inductance, possessing resistance, is joined in parallel with a capacity (see Fig. 17). The expression for the impedance of this circuit is very complex and we shall only be concerned with the impedance at the resonant state. At resonance the impedance is a *maximum*, and resonance occurs when the condition expressed by (18) and (24) obtains. Since the parallel

circuit behaves in a manner similar to that of the series circuit at or near the resonant frequency it is often represented by the simpler series circuit for ease of manipulation.

We have seen that the series circuit can be used as a wave-trap. In a similar way, the parallel circuit can be connected in *series* with the aerial lead to a receiver (see Fig. 18) and tuned to the wavelength of the local station, or of any interfering station, so that the interfering signals are rejected. The circuit offers maximum impedance—which is very large—to these signals, and hence almost completely prevents their operating the receiver. Signals of wavelengths greater or less than the resonant value are almost unaffected and operate the receiver in the normal manner.

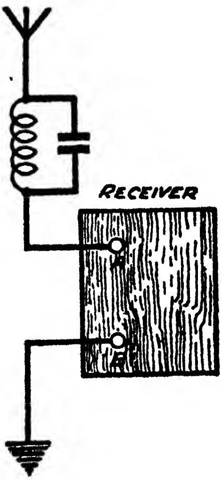


FIG. 18.—HOW A PARALLEL CIRCUIT CAN BE USED AS A WAVETRAP.

Effect of Resonance on a Parallel Circuit

Now consider the parallel circuit of Fig. 17 when resonance occurs. As already stated, it can be represented by the simpler series circuit and it is re-drawn in this way in Fig. 19, the signal source now being in series with the two circuit elements. We shall suppose that the voltage of the signal source is e_s. Provided that no current is taken from the circuit at A and B, the same current will pass through both L and C. Let this current be i. Suppose that the voltage across the terminals A and B is used for operating a receiver. We have to find the voltage across AB in terms of the input voltage (e_s), and the inductance and capacity of the circuit.

At resonance $L\omega = \frac{1}{C\omega}$, hence the impedance of the circuit is R, the pure resistance of the coil, and thus, by Ohm's law we have :—

$$e_s = iR \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Now the impedance of the portion AB of the circuit is :—

$$Z = \sqrt{R^2 + (L\omega)^2}$$

In practice R is very small compared with $L\omega$ (certainly less than $\frac{1}{8}$th of $L\omega$), hence R^2 can be neglected in this expression, giving :—

$$Z = L\omega$$

Now the voltage produced across the ends of a circuit of impedance Z and carrying current i is equal to the product of i and Z. Hence :—

$$e_{AB} = i\,Z$$

i.e.,

$$e_{AB} = i\,L\omega \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

where e_{AB} is the voltage across AB.

Dividing (25) into (26), we see that :—

$$\frac{e_{AB}}{e_s} = \frac{i\,L\omega}{iR}$$

i.e.,

$$\frac{e_{AB}}{e_s} = \frac{L\omega}{R}$$

i.e., the ratio of the voltage across AB to the input voltage is equal to $\frac{L\omega}{R}$.

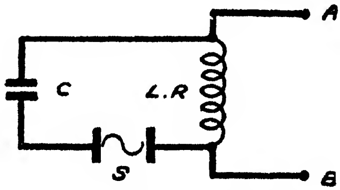


FIG. 19.—SHOWING THE SIGNAL SOURCE IN SERIES WITH THE TWO CIRCUIT ELEMENTS.

Magnification Factor

We have already seen that R is generally very much smaller than $L\omega$, and hence $\frac{L\omega}{R}$ is much greater than 1. That is to say, the voltage operating the receiver is much greater than the input voltage. In other words, the tuned circuit has resulted in a magnification of the voltage. The expression $\frac{L\omega}{R}$ is the amount by which the input voltage has been magnified and is known as the MAGNIFICATION FACTOR of the coil. We shall employ m as a shorthand notation for the magnification factor of a coil. In the expression $\frac{L\omega}{R}$, L is in henries, R is in ohms, and ω is the angular frequency of the current, and equals 2π times the frequency in cycles per second. In the case of coils used in medium wave tuning circuits, m usually has a value between 100 and 250, the actual value depending on both the construction of the coil and the effect of the circuit in which it is connected.

Note that, since we are concerned with the condition of the circuit *at resonance*, we may write ω_0 for ω, and we may then replace $L\omega$ by $\frac{1}{C\omega}$, $\left(\text{at resonance } L\omega = \frac{1}{C\omega}\right)$ thus giving :—

$$m = \frac{L\omega_0}{R} = (\text{also}) \frac{1}{RC\omega_0}.$$

Also

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

and hence $\frac{L\omega_0}{R}$ becomes $\frac{L}{R} \times \frac{1}{\sqrt{LC}}$ — *i.e.*, $\frac{1}{R}\sqrt{\frac{L}{C}}$

which is yet another way of expressing the coil magnification factor.

Let us find the magnification factor of a coil of inductance 250 mH. employed in a medium-wave tuning circuit. If we find the value of m corresponding to wavelengths of 300, 400, 500 and 600 metres, this will be sufficient to show how m varies with wavelength. These wavelengths correspond to frequencies of 10^6, $7{\cdot}5 \times 10^5$, 6×10^5, and 5×10^5 cycles per second, and hence the angular frequencies are $2\pi \times 10^6$, $2\pi \times 7{\cdot}5 \times 10^5$, $2\pi \times 6 \times 10^5$, and $2\pi \times 5 \times 10^5$, *i.e.*,

$$\begin{aligned}
&2 \times 3{\cdot}14 \times 10^6 &&= 6{\cdot}28 \times 10^6 \\
&2 \times 3{\cdot}14 \times 7{\cdot}5 \times 10^5 &&= 4{\cdot}71 \times 10^6 \\
&2 \times 3{\cdot}14 \times 6 \times 10^5 &&= 3{\cdot}77 \times 10^6 \\
\text{and}\quad &2 \times 3{\cdot}14 \times 5 \times 10^5 &&= 3{\cdot}14 \times 10^6
\end{aligned}$$

The H.F. resistance of the coil depends on the frequency of the signal—*i.e.*, on the wavelength—and we shall take the following H.F. resistance values as typical of a well designed coil wound with Litz wire. The additional resistance introduced by the effect of the valve with which the coil is used has been taken into consideration.

Wavelength (metres).	H.F. Resistance (ohms).
300	10·0
400	6·0
500	4·0
600	3·0

Thus we have :—

$$m = \frac{250 \times 6{\cdot}28 \times 10^6}{10^6 \times 10} \text{ at 300 metres}$$

i.e., $m = 157$ at 300 metres.

Repeating the calculation for the other wavelengths, we obtain the following results :—

Wavelength (metres).	Coil Magnification Factor (m).
300	157
400	196
500	236
600	262

Thus we see that an induced signal voltage of 1 millivolt is magnified by the coil to 157 millivolts at 300 metres, and to 262 millivolts at 600 metres. For a given signal strength, therefore, the receiver response improves as the wavelength is increased. With another type of coil the value of m will, of course, increase at a different rate.

Tuning Coils

The design and form of the tuning coils have an important bearing on the sensitivity and selectivity of the receiver for which they are employed. The tuning coils also have a considerable effect on the quality of loudspeaker reproduction. This is due to the fact that a signal is not made up of a single freq bigger as the musical frequencies occupy a certain band width on three- side of the mean carrier wave frequency. to the

Actually they extend for about 4½ kc/s. on each sid nomen- therefore, with excessively sharp tuning, the reproduc number impaired as the response to higher musical notes, or freq of their is diminished. The result is that although the low n ceived at full strength the higher ones are prop un before duced in intensity. this form

This fault can be rectified to some extent by the use is anything

Without entering into the theory of band-pass tuning it will be sufficient to say that the tuned circuits are so arranged that although they produce a high degree of selectivity, they always give equal response to a band of frequencies. In most cases a 9 kc/s. band width is chosen so that all musical notes will produce an equal response, and also because 9 kc/s. is the separation allowed between all high-powered European transmitters.

Screened Coils

In any receiver employing more than a single coil, screening is practically essential. For this reason, nearly all manufacturers now supply sets of coils enclosed in aluminium screening cans. When using screened coils it should be remembered that the screens must be earth connected or otherwise they cannot be completely effective. The function of the screening can is that the current induced in it from the tuning coil sets up a magnetic field in opposition to that due to the coil so that the magnetic field outside the screen and, consequently, interference between coils is greatly reduced.

CHAPTER XI

VALVES

THE thermionic valve in its present highly developed form owes its origin to a number of basic discoveries and an infinite amount of organized research; there are, however, two contributions which are so fundamental in character that it would be improper to pass them by without specific mention. The first of these was the epoch-making discovery of Professor Thomas A. Edison, in 1883, which revealed that certain substances heated in a vacuum to more or less critical temperatures emitted electrons, although at the time they were presumed to be charged particles of matter carrying a negative sign since the great scientist discovered that these newly-discovered particles were attracted by an electrode within the enclosed vacuum which was held at a potential, positive in respect to the emitter. Although this discovery, which in effect gave the diode valve to mankind, was undeniably of great importance, it added nothing that mitigated the difficulties of amplifying electromagnetic waves until, in 1907, Lee de Forest conceived the idea of interposing a mesh or grid between the emitter (called the cathode) and the "collector" electrode (called the anode) which enabled the valve to amplify, since by suitable arrangement a change of voltage fed to the grid produced a similar but bigger change of voltage at the anode. Lee de Forest called his three-electrode valve the audion, a term which has given place to the word triode, since it has become fashionable to choose nomenclature for valves which give some indication of the number of electrodes they comprise and consequently a hint of their purpose.

The steady development of valve design had begun before the 1914–18 war, which gave considerable impetus to this form of progress, and probably marked the first steps towards anything approaching consistency between identical types. A steady in-

specific requirements has followed, almost all of which is due to continuous research on the part of British and American valve manufacturers, with some important contributions from the Continent.

The manufacture of the modern complex range of valves is highly specialized and calls for meticulous care from the analysis of raw material on its arrival at the factory to rigorous testing of the finished product. It is not proposed to enlarge on the birth of the valve, since both historical and manufacturing aspects are fully dealt with in numerous works, but it is worth while to mention that a modern mains receiving valve may use upwards of sixty separate materials in its manufacture, all of exceptional purity and the gas pressure left in the bulb after pumping is equal to about one ten-millionth of atmospheric pressure.

ELECTRON EMISSION

Electron or thermionic emission, as we have already mentioned in previous chapters, is dependent on the property of throwing off electrons exhibited by certain materials when heated to a suitable temperature. A metal unaided by chemical coating, such as tungsten must be raised to a temperature of about 2,200°C (approaching white heat) before worth-while emission occurs ; it is conventional therefore to use a wire or in the case of the indirectly heated valve, a fine gauge tube coated with chemicals which emit electrons at a more convenient temperature, namely at about 800°C. This gives a dull red heat not to be confused with the temperature of the heater wire running through the thin coated tube in the case of the indirectly heated valve which works at a temperature more appropriately described as bright red. The precise nature of these highly emissive coatings are still closely guarded manufacturing secrets but the basic chemicals which the electronic chemist automatically associates with low temperature emission are barium and strontium oxides which are both to be found in ordinary plain earth. Other electrodes, described later, are made of a variety of metals in which nickel, nichrome and copper predominate.

A valve, in the normally accepted sense of the word, will employ either a filament or cathode as a source of electronic emission. A filament

heated mains valves employ a cathode and heater as shown at Fig. 1 (*b*). The electrical difference is that the emissive coating and source of heat are in continuous electrical contact whereas in the indirectly heated valve the emissive coating is held on a fine gauge metal tube surrounding a heater wire which is usually insulated from the tube by a porcelain coating. This arrangement prevents change in electronic emission caused by the fluctuating alternating current which heats the heater wire due to the temperature inertia of the cathode and also prevents the alternating

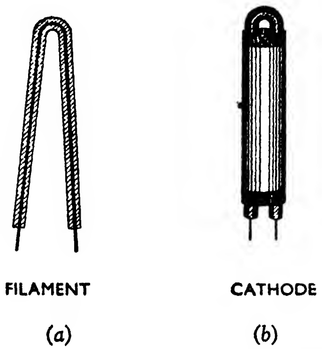


FIG. 1.—CONSTRUCTION OF VALVE FILAMENT AND CATHODE.

(*a*) Filament showing coating exaggerated.

(*b*) An exaggerated representation of a cathode showing the insulated heater inside the emissive coated cathode tube.

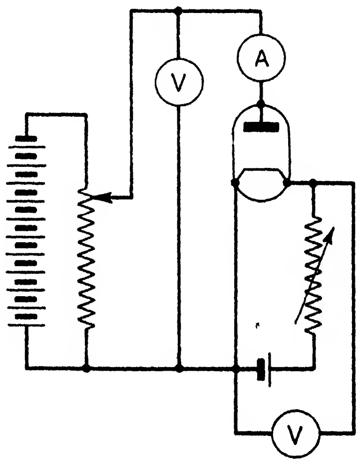


FIG. 2.—A SIMPLE CIRCUIT TO INVESTIGATE THE BEHAVIOUR OF A DIODE VALVE.

voltage across the heater from influencing the grid through capacity since in most circuits the cathode can be held sensibly at earth potential from the A.C. point of view. In all following explanations in this chapter the word cathode will unless otherwise specifically stated, imply filament or cathode to obviate the constant repetition of this irritating phrase.

THE DIODE

As already implied in the introductory remarks above, the diode is a two electrode valve having a cathode and anode; providing that the cathode is raised to emission temperature and the anode held at a suitable positive potential, electrons will

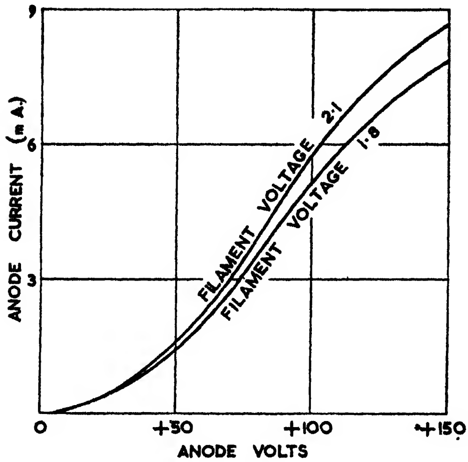


FIG. 3.—THE CHANGE OF ANODE CURRENT CONSEQUENT UPON THE CHANGE OF ANODE VOLTAGE.

Taken at two filament temperatures.

flow from cathode to anode and back through the power supply to cathode as an electronic current. The value of this electronic current will be affected by cathode temperature and anode potential; in fact, the change of anode current will be directly proportional to the change of anode potential over a certain range of the latter. It will be instructive, therefore, to arrange a circuit which will permit variation of anode voltage and cathode temperature and register the resultant change in electronic current. Such a circuit is shown at Fig. 2, in which a diode of the directly heated type having a filament has been selected in order to postpone to a more convenient moment the explanation of a certain phenomenon. Reference to Fig. 2 will show that both filament and anode voltage can be varied and the value selected ascertained from the appropriate voltmeters and by selecting a filament voltage and progressive series of anode voltage it will be possible

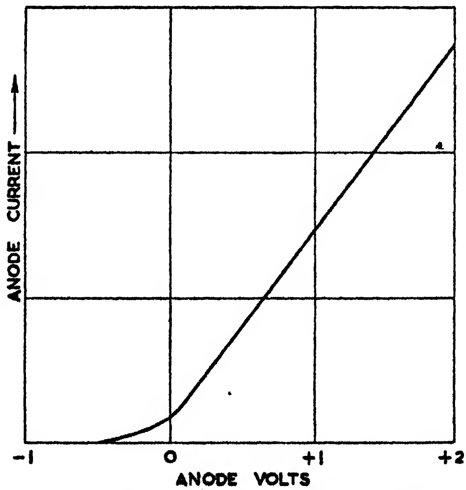


FIG. 4.—THE CHANGE OF ANODE CURRENT CONSEQUENT UPON THE CHANGE OF ANODE VOLTAGE OF AN INDIRECTLY HEATED DIODE.

Selected to show that anode current may start when the anode is slightly negative.

to plot a performance curve, a typical example of which is shown at Fig. 3, two such curves being plotted, the lower with a filament voltage of 1.8 and the upper curve 2.1. Note particularly that the more efficient curve with the higher filament voltage gives a bigger value of current for a given anode voltage.

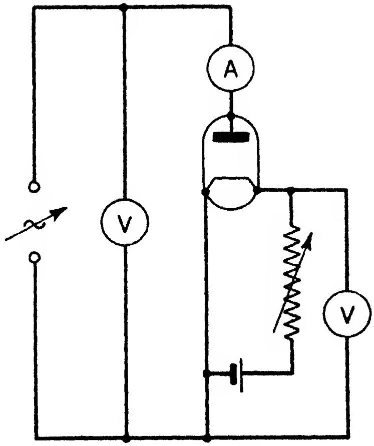


FIG. 5.—A DIODE ARRANGED TO SHOW ITS BEHAVIOUR WITH A.C. ANODE VOLTAGE.

To permit observation the periodicity must be very low, say 1 cycle in 15 seconds.

Contact Potential

If the diode valve at Fig. 2 is changed for one of the indirectly heated type, a phenomenon called contact potential will almost certainly appear which greatly confuses the simple explanation that electrons will flow from cathode to anode only when the latter is positive in respect to the former. Due to contact potential the voltages applied externally to the valve will not be the same as that obtaining across the actual electron stream within the valve which brings about the curious effect that electrons will actually flow from cathode to anode when the latter is apparently slightly negative in relation to the former. Such a condition is illustrated at Fig. 4 which shows the characteristic of a diode valve of the indirectly heated type ; it will be observed that with the example selected, current commences to flow when the external voltage difference between cathode and anode is 0.5 volt negative and increases as the anode voltage is made less negative or, speaking conventionally, more positive. The phenomenon of contact potential which is not peculiar to the diode, is important, since as will be seen later it plays a part in the functioning of more elaborate valves. The type of valve chosen for the purpose of plotting the curve at Fig. 3 was selected solely on the grounds that anode current commenced to increase exactly from zero in the positive direction but as will be seen later, contact potential has been in a sense reversed in certain multi-electrode battery valves so that current does not flow

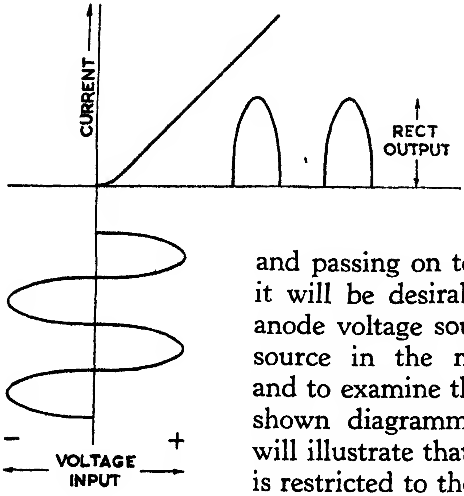


Fig. 6.
This Diagram illustrates the Principle of Rectification.

from the filament to the electrode nearest to it until the latter is half a volt or more positive in respect to the filament, a condition which gives material advantages.

Before leaving the diode and passing on to more complicated types, it will be desirable to substitute the D.C. anode voltage source in Fig. 2 for an A.C. source in the manner shown at Fig. 5 and to examine the behaviour of the diode, shown diagrammatically at Fig. 6 which will illustrate that the flow of anode current is restricted to the positive half cycle of the alternating voltage applied to the anode. It follows, therefore, that although an alternating voltage is applied to the anode, current flows in one direction only or in other words is direct current, admittedly intermittent and of rhythmically varying amplitude, but nevertheless direct current, thus demonstrating that the diode can be employed as a rectifier.

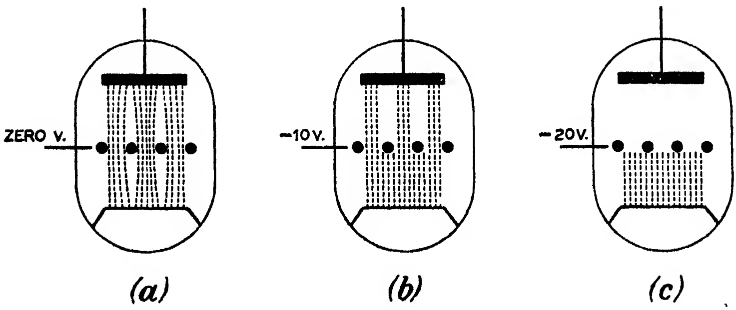


Fig. 7.—An Attempt to show diagrammatically how the Grid controls the Electron Stream.

(*a*) No bias.
(*b*) Normal working bias.
(*c*) High negative bias.

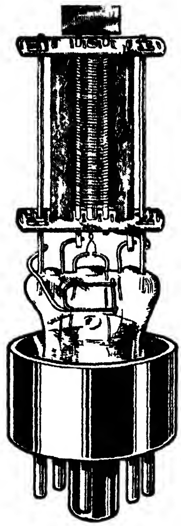


FIG. 8.—ELECTRODE ASSEMBLY OF A MAZDA TRIODE.

Anode cut away to show the cathode surrounded by the grid.

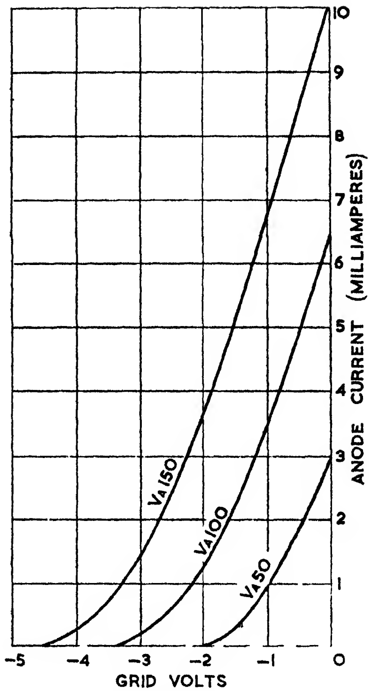


FIG. 9.—CHARACTERISTIC CURVE OF A TYPICAL TRIODE TO ILLUSTRATE THE TEXT.

THE TRIODE

The triode is in effect a diode valve with an electrode of open construction interposed between cathode and anode and by virtue of being placed closer to the cathode than the anode, it exercises proportionately greater control which enables the valve to act as an amplifier because this greater control will allow a change of voltage applied to the grid to bring about a bigger change in anode current than would be caused by a similar change in anode voltage. Fig. 7 attempts to show pictorially the effect of grid potential on the electronic current. The illustration (*a*) portrays the electron stream when the grid is held at cathode potential, (*b*) when the grid is held at normal negative bias voltage and (*c*) with sufficient negative bias to prevent altogether the passage of electrons. The manner in which the grid surrounds the cathode can be seen by referring to Fig. 8.

Amplification Factor

It is obvious that the triode can be investigated in the same manner as was adopted for the diode by using the same circuit as that shown at Fig. 2 with means of varying the grid potential and noting the value selected. The curve of a typical triode taken in this manner is shown at Fig. 9 which gives the value of anode current for any value of grid voltage under conditions of three selected anode voltages and it will be interesting to compare the relative influence of grid and anode voltage upon anode current. A change of anode voltage from 50 to 150 (at zero grid bias) will change the anode current from 3 to 10 milliamps, approximately, which is a change of 7 milliamps or a change of 0·07 milliamps for each volt of change. It is now necessary to discover the effect on anode current of a change of grid voltage at, say, an anode voltage of 100 volts which is the mean or average between the voltages already used of 50 and 150. Reference to Fig. 9 will show that with an anode voltage of 100 the valve passes 6·5 milliamps at zero grid bias and 3·5 milliamps at 1 volt negative bias, thus a change of 1 grid volt has brought about a change of 3 milliamps which is a marked contrast to a change of 1 anode volt which brought about a change of 0·07 milliamps. It is fairly obvious that if 0·07 (the change due to a change of 1 anode volt) is divided into 3 (the change due to 1 grid volt), the figure so obtained will indicate the superiority of the grid over the anode or to use the correct term, the amplification factor. The actual figure arrived at in this manner is 43 which, considering the small scale of the curve at Fig. 9 and consequent possibility of minor error, compares very favourably with the published figure since the curve is that of a Cossor 41 MTL and the manufacturers rated amplification factor is 45, taken with an anode voltage of 100 and grid voltage zero, a condition which has been closely approximated by the conditions above.

Impedance and Slope

The figures selected to demonstrate the real meaning of amplification factor can be used to ascertain the related characteristics of impedance and slope. Impedance is the equivalent alternating current resistance of the electron stream and like any other variant of Ohms Law, anode impedance can be ascertained by the effect of voltage on current, and in its present form

is arrived at by dividing a selected change of anode volts by the resultant change in anode current. It will be remembered that in the example previously used, a change of anode volts of 100 volts brought about a change of 0·07 milliamps and division of 100 volts by 0·07 milliamps will give the impedance but before the actual calculation is undertaken, cognisance must be taken of the fact that units are not equable since potential is in volts and current is in milliamps. The logical step would be to express 0·07 milliamps in terms of amps. but it is very much more convenient to divide 0·07 into 100 and compensate for the fact that one of the units is in milliamps, by multiplying the answer by 1000. It is now possible to ascertain impedance by dividing 100 by 0·07 which is 14·3 which, when multiplied by 1000 for reasons already stated, gives a figure of 14,300 ohms which again is close to the makers' rating of 15,000 ohms.

Slope, or mutual conductance, can be ascertained by a direct inspection of the curve, or by combining impedance and amplification factor. Slope is a means of annotating directly the change of anode current to be expected from a stated change of grid voltage and is expressed as so many milliamps change, per volt change. Inspection of Fig. 9 will show that a change from zero to 1 grid volt will change the anode current (at an anode voltage of 100) from 6·5 to 3·5 or a change of 3 milliamps which is 3 milliamps per volt or to use the normal abbreviation 3ma/V. Slope is a true measure of the efficiency of the valve in itself and it is interesting to note from Fig. 9 the varying efficiency of the valve with different anode voltages. It will be seen that with an anode voltage of 50, a change from zero to 1 grid volt only brings about a change of 2·1 milliamps, whereas at 150 anode volts the change is 3·3 milliamps ; it is obvious, therefore, that a statement of a valve characteristic must be accompanied by the condition obtaining when the measurement was made. The alternative method of ascertaining slope is to divide the amplification factor by the impedance and multiply the answer by 1,000 since the figure required is to be in milliamps and not amps. per volt, thus the slope arrived at in this way from the figure of 14,300 ohms and the amplification factor of 43 is almost exactly 3 milliamps per volt.

It has been stated that slope is a direct indication of *' efficiency or goodness of the valve and at first thought it *r* seem that amplification factor is a similar indication bu'

not so since amplification factor means little unless impedance is taken into account. For example, a valve with an impedance of 30,000 ohms and an amplification factor of 90 still has a slope of 3ma/V so the doubling of the amplification factor has been offset by doubling the impedance and no advantage is thereby gained unless a valve of higher impedance can be used to greater advantage.

The reason for involving the reader in intricacies of valve characteristics is primarily because they so readily demonstrate the function of grid and anode on the electron stream and with little imagination, present a mental working picture. American valve characteristics substitute slope or mutual conductance for transconductance which gives the same indication of valve efficiency but is expressed differently since it is derived from the ability of the electron stream to conduct, as opposed to resist, and is given not in milliamps per volt but in mho which is a unit of conductance appropriately derived by spelling ohm backwards, which is the unit of resistance. In actual practice the micromho is used which as might be imagined is one millionth of a mho. Transconductance is obtained by dividing the change of anode current by the change of grid voltage thus, using figures already quoted above for illustrating characteristics, a change of 1 grid volt brings about a change of 3 milliamps which is 0·003 amps. which divided by 1 gives a transconductance of 0·003 mhos or 3,000 micromhos. To convert transconductance to slope divide the number of micromhos by 1000 and the answer will be the number of milliamps per volt.

Anode Load

In order that the valve may develop its maximum efficiency it must be given the correct amount of work to perform and only this optimum condition will produce maximum efficiency. A contemporary once illustrated this fact with a particularly striking analogy of an ordinary railway engine ; if a railway engine is grossly under-loaded and proceeds with one passenger sitting on the buffer, the energy expended by the engine will be considerable but the task achieved almost negligible. The opposite effect, a locomotive so grossly overloaded that at the end of the day it has only struggled a few hundred yards, brings about the same condition, namely that the locomotive has expended great energy but the task achieved is almost negligible. The measure

of the performance of a valve with its associated components is referred to as stage gain which is, in effect, the amplification of the complete stage or single valve section of a receiver.

The Triode as L.F. Amplifier

Fig. 10 shows the skeleton circuit of a triode valve arranged in the simplest possible manner to act as an amplifier and it is necessary to determine what conditions will enable the valve to perform this function to the greatest advantage since it may be presumed that the cathode will be heated to its correct working temperature. It is obvious from previous remarks that increased anode voltage gives increased performance and will, therefore, be limited only by the maximum safe figure recommended by the manufacturer; it remains, therefore, to ascertain the steady grid potential and the resistance of the anode load. The purpose of applying a fixed grid potential or grid bias is to enable the valve to function in a symmetrical manner since it may be presumed for the time being that the output from the stage is required to be similar in every respect to the input except for amplitude which should be as great as possible. Fig. 11 (*a*) show the result of attempting to amplify with the grid held at cathode potential.

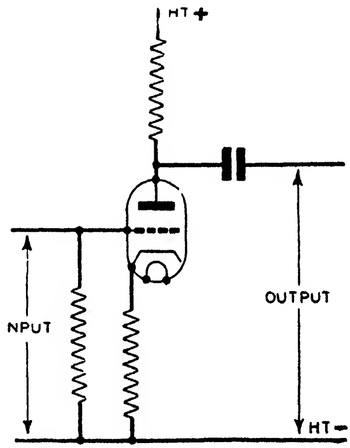


FIG. 10.
ILLUSTRATING THE PRINCIPLE OF A TRIODE AS AMPLIFIER.

It will be observed that while one half of the input waveform remains unaltered, the half that swings the grid in the positive direction is seriously foreshortened, due to the valve taking grid current, thus robbing the anode of electrons which would otherwise have travelled to it and also due to the fact that the flow of grid current has influenced the grid potential. This illustration assumes that the valve is so designed that grid current commences at zero grid voltage and is used in the manner illustrated in Fig. 10. This type of distortion is sometimes colloquially referred to as "gridding." Fig. 11 (*b*) illustrates the

other extreme where the grid is held at a potential so negative in respect to the cathode that the negative half of the input swing is working on the curved portion of the valve characteristic and part of the swing goes past cut-off; this results in foreshortening the input waveform due to the curvature of the valve characteristic while the peaks are cut off altogether when the input swings past the cut-off point. Clearly there is a condition between these two extremes of bias where optimum working will be obtained. This point is usually midway between the point where serious curvature begins on the one side and where grid current begins on the other side. This condition is illustrated at Fig. 12 which shows the same grid-volt/anode-current curve as that shown at Fig. 9, but with the addition of a grid current curve which unfortunately is seldom included by valve manufacturers ;

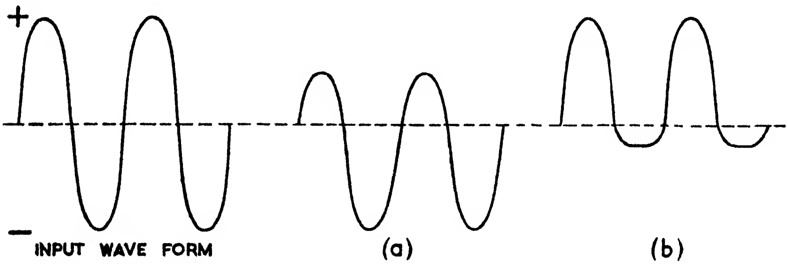


FIG. 11.—DIAGRAMMATIC REPRESENTATION OF DISTORTION.
(*a*) Due to inadequate bias voltage and (*b*) Excessive bias voltage.

as it happens, however, the commencing point of grid current does not vary very widely. Valve manufacturers quote the correct bias to be used for various anode voltages and for normal purposes this is the optimum value to employ, it being necessary to bear in mind that the anode voltage is the voltage existing between anode and cathode and not the applied voltage since the latter will be greater than the former by the voltage drop across any components between anode and H.T. + and cathode and H.T. −. Occasions when manufacturers' recommendations will be modified, will normally be confined to battery receivers where maximum grid bias will be used consistent with good quality reproduction in the interest of H.T. economy and in certain classes of push-pull output which is dealt with elsewhere.

The calculation of stage gain is comparatively simple when the anode load is a pure resistance, but when the anode load is

inductive complications are introduced which are beyond the scope of this book and furthermore, it is not thought that readers will desire to enter into mathematical considerations of stage gain, but rather to have some knowledge of the influence of anode load in general terms in order to be aware of components which can usefully be the subject of experiment. In order, therefore, to complete the picture, a curve is included at Fig. 13 which, using the now familiar MTL valve shows the stage gain to be expected with various anode loads, the circuit arrangement being that shown at Fig. 10, the anode voltage being 100 and the grid bias optimum. Clearly, greater stage gain could be obtained with an increased anode voltage, but the figure of 100 was selected as this value has been the basis of previous explanation. It must be understood that when taking the curve at Fig. 13 (*a*) the applied anode voltage was varied appropriately with each change of anode resistance so that the voltage difference between anode and cathode was at all times 100 volts. Curves (*b*) and (*c*) were taken with different voltages held constant at the H.T. + end of the anode load.

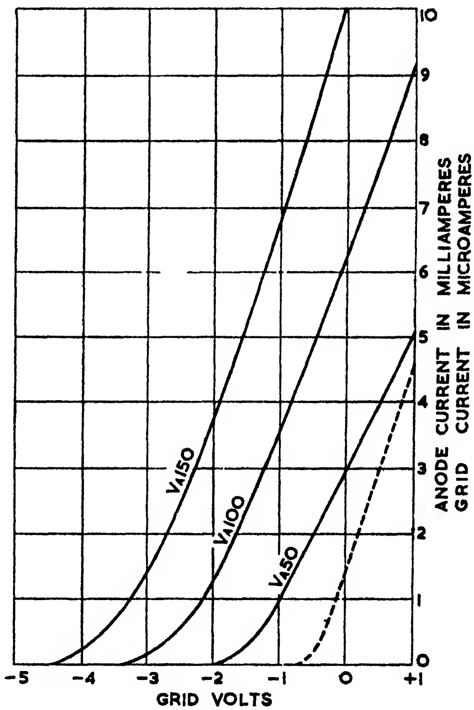


Fig. 12.

The Curve shown at Fig. 9 extended to show Grid Current (dotted line).

The Triode as R.F. Amplifier

Before investigating more elaborate types of valves, it is convenient to consider the triode as a high-frequency amplifier in order to illustrate the reason why other types of valves are preferable for performing this office. Fig. 14 shows a rearrangement

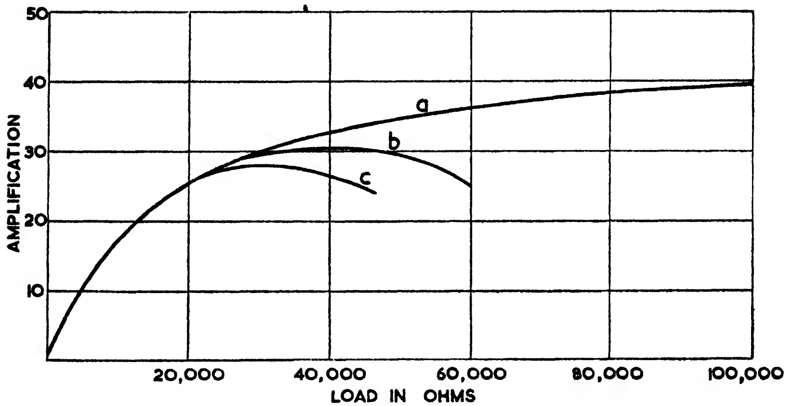


FIG. 13.—RELATIONSHIP BETWEEN ANODE LOAD AND AMPLIFICATION.
(*a*) With constant voltage at anode ; (*b*) and (*c*) with different voltages held constant at external end of load.

of Fig. 10 whereby tuned inductances replace both the input circuit and output circuit resistors. Providing that the inductances are even moderately well designed, and tuned to the same frequency, high stage gain could result, but is limited by the Miller effect which causes the valve to oscillate, that is to say the valve will generate a high-frequency current without any high-frequency energy being fed in from an external source. The valve will, in fact, behave as a miniature transmitter. This phenomenon is due to energy in the anode circuit feeding back into the grid circuit which causes a build up since such fed back energy will again appear in the anode circuit duly amplified and will again be fed back into the grid circuit and the vicious circle continues. This feeding back of energy can obviously take place due to magnetic coupling between the anode and grid inductances,

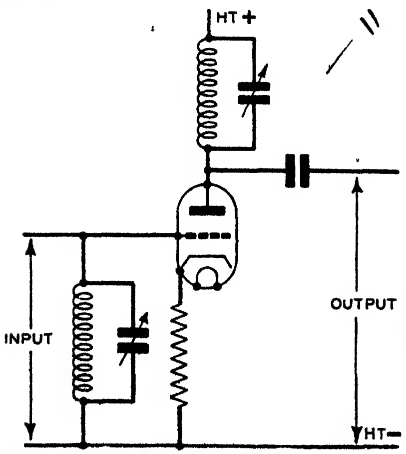


FIG. 14.—ILLUSTRATING THE PRINCIPLE OF A TRIODE AS RADIO-FREQUENCY AMPLIFIER.

but this possibility can be and in fact usually is, countered by enclosing either or both in metal boxes duly earthed, or preventing magnetic coupling by some other convenient method; screening, however, does not prevent the trouble and clearly energy must be fed back through some other avenue which is capacity existing between the anode and grid. As coupling between the inductances can be prevented by interposing a metal screen, it is perhaps logical to prevent coupling between anode and grid by interposing a screening electrode between them, but as will be seen, the presence of a screen in the vital electron path brings about a number of other changes in addition to the one desired which is the reduction to very small limits of grid to anode capacity.

THE TETRODE

A triode with an electrode interposed between grid and anode is called a tetrode which is a generic name for such a valve in two radically different forms intended for radio-frequency amplification and for use in the output stage; for the time being the latter application will be ignored and attention focused on the radio-frequency tetrode or to use the normal nomenclature, the screened grid valve. Since this additional electrode is a grid it is necessary to differentiate from the grid to which the signal is applied, consequently the latter is termed the control grid and the former the screen grid. Fig. 15 gives an exploded view of a typical screened grid valve from which two interesting facts may be readily observed. The screen grid almost completely surrounds the control grid using solid metal at top and bottom, the actual grid formation being reserved for the area between cathode and anode to permit the passage of electrons. It is also

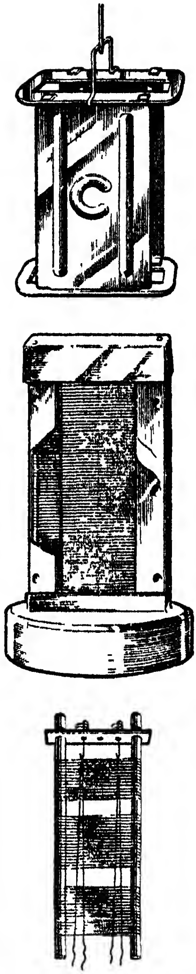


FIG. 15.—EXPLODED VIEW OF THE COSSOR 220 VSG.

Electrodes are (*top*) anode, (*middle*) screening grid and (*bottom*) control grid.

apparent that the screen grid has a very small mesh compared with the control grid and may therefore be expected to have a profound effect on the characteristics of the valve, an expectation which is fully realized. Even though the screen grid is a mesh its efficiency as a capacity screen is far greater than might be expected; in one well-known type of battery screened grid valve, the total capacity between grid and anode is only 0·001 p.f. which is roughly equal to the capacity between two sixpences placed at a distance of twenty feet, a remarkable tribute to the efficiency of the screening grid.

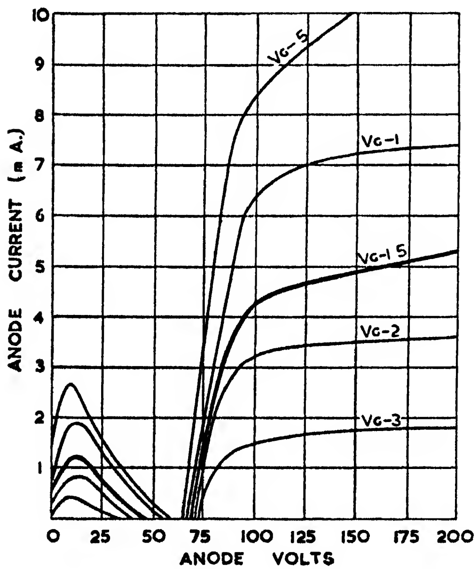


Fig. 16.—The Change of Anode Current consequent upon the change of Anode Voltage of an Indirectly heated Screen Grid Valve taken at five different Grid Voltages. (Cossor MSG/LA.)

Characteristics

Fig. 16 shows the anode - current / anode - volts curve of an indirectly heated screened grid valve and it will be well to explore this curve point by point. Commencing at zero anode volts and reading from left to right, a change from zero to 10 volts brings about a very sharp increase in anode current but further increase of anode voltage produces the reverse effect and anode current decreases as anode voltage increases, a phenomenon which is known as negative resistance, the reason for the choice of terminology being obvious. Continuing the examination of the curve, a point is reached around 50 volts when the flow of anode current ceases altogether and with a slight further increase reverses and the electronic current flows away from the anode instead of towards it. Yet another small increase produces a very sharp rise in current, followed

by continuous increase of less steepness until the curve eventually approaches the horizontal.

The reason for this most remarkable negative characteristic kink is interesting. It must be understood that when taking the curve at Fig. 16, the screen voltage was maintained at a constant figure, namely 80 volts. The electron stream must pass through the mesh of the screen grid on its way to the anode and since the screen grid is held at a potential substantially positive in respect to the cathode, the electrons are subjected to considerable acceleration and strike the anode at considerable velocity; there comes a point, therefore, when the acceleration of the stream and the pull of the anode causes the electrons to hit the anode with such violence that either or both of the following effects occur: (i) The electron bounces off the anode and is attracted to the most powerful force in its vicinity which is the screen or, (ii) The electron hits the anode with such violence that it knocks one or more electrons out of the anode which are attracted to the biggest force in the vicinity which as already stated is the screen.

The critical point where this bouncing back or secondary emission begins, in the curve under review, is at approximately 10 volts on the anode and further increase of anode voltage increases the effect until the anode voltage approaches the screen voltage in value, when the anode is able to hold its own and the screen is unable to drag electrons from the vicinity of the anode. It is very difficult to give a true picture of the behaviour of the screened grid valve under working conditions since the arrangements for maintaining constant screen voltage in the average receiver are only partly effective and the flow of electrons to the screen grid described above will vary the screen voltage and produce various changes in the shape of the anode-current/anode-volts curve. It is apparent, however, that the very undesirable kink in the anode characteristic of the screened grid tetrode greatly limits the ability of the valve to handle a large input.

Cross Modulation

Inability of a valve to handle a given input must take the form of distortion and if this distortion takes the form of serious or complete foreshortening of one half of an alternating current,

rectification is present in partial or complete form. Rectification in a radio-frequency amplifier produces an extremely undesirable condition known as cross modulation which may be described as the super-imposition of an unwanted signal on the wanted signal even though their frequencies differ. Once this phenomenon has taken place, any tuned circuits which follow, are powerless to reduce the interference of the unwanted station as both the wanted programme material and the unwanted material are on the same frequency. It is perhaps easier to understand cross modulation when its practical effect is understood. Assume that the wanted signal is 1,000 kcs. and the unwanted signal 1,025 kcs. and when listening to the former, interference is experienced from the latter. If, when the wanted station closes down the interfering station is heard, then the tuned circuits employed are obviously inadequate to give the required separation but if when the wanted station closes down the unwanted disappears also or is reduced in strength then cross modulation is present.

To summarize, it is apparent that the screened grid valve is too easily overloaded under conditions which are easily experienced in normal practice. It is also apparent that the very low capacity existing between control grid and anode will permit the valve to develop very high stage gain with stability, i.e. without the valve oscillating on its own account. Maximum possible stage gain is limited by the inter-electrode capacity, small though it may be and since the reactance of this capacity will vary with frequency, it follows that maximum stage gain will vary with frequency; as a rough guide, however, it is possible to design a stage to give a gain of 4,000 times for a single valve although the attainment of such a figure requires *quite unusual* circuit design both as regards screening and coil design; it is unusual, however, to attempt such a figure and a gain of 700 for a single stage or a gain of 400 per stage when two or more stages are used, can be regarded as a very favourable achievement in normal circumstances.

It is apparent that the usefulness of the screened grid tetrode could be increased if the negative resistance kink could be abolished and this desirable modification is available in a form known as the screened pentode, sometimes called the Radio-frequency Pentode.

THE PENTODE

It will be recalled that the cause of the kink in the screened grid valve is secondary emission from the anode, the electrons arising from which are attracted by the screen; in the pentode valve an additional grid called the suppressor grid is interposed between the anode and screening grid and is normally connected to the cathode either within the valve itself or externally. The suppressor grid greatly reduces the power of the screen grid to draw electrons from the vicinity of the anode since electrons so placed will be attracted by the anode and repelled towards it by the suppressor grid, or expressed another way, electrons in the vicinity of the anode would have to run the gauntlet of the relatively negative suppressor grid to reach the screen grid. So successful is the suppressor grid that the kink is virtually eliminated as may be seen from an examination of a typical screened pentode curve at Fig. 17. It will be noted that the suggested working curve shown in *heavy* line is substantially straight from 50 anode volts upwards and since the presence of an anode load will increase the straightness of the curve, and bearing in mind the gradual way in which curvature begins, acceptable working conditions will commence below 50 volts.

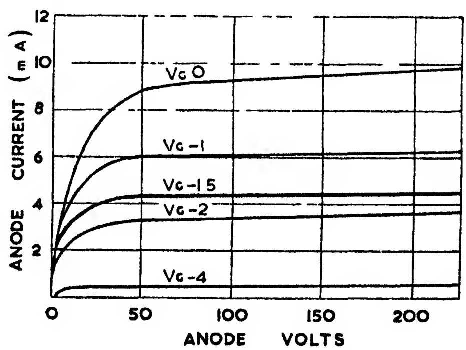


Fig. 17.—The change of Anode Current consequent upon the change of Anode Voltage of an indirectly-heated Pentode Valve taken at five different Grid Voltages.

Before passing on to a more detailed consideration of the screened tetrode and pentode as radio-frequency amplifiers, the opportunity can be taken to mention that other secondary effects can occur both in screened valves and those of other types due to electrons being thrown off from a variety of objects which have become heated on account of the general rise in valve temperature. This danger is countered by coating appropriate surfaces with carbon which is a very poor emitter of electrons at temperatures likely to be experienced. This treatment is often

met with on anodes of radio-frequency screened pentodes, and other types and may be identified by the black matt surface of carbonized metal in contrast to the ordinary bright surface. The bulb is sometimes coated internally with carbon for the same reason.

The Radio-frequency Amplifier

In the following remarks on the radio-frequency amplifier, the screened pentode is used throughout, it being understood that the screened grid tetrode can be used as an alternative with the attendant short-comings of that type of valve and, generally speaking, lower all-round efficiency. It is difficult to deal in some detail with the radio-frequency amplifier entirely divorced from other stages in a receiver since requirements are not apparent; it will be useful, therefore, to tabulate the three main sections of a receiver together with the most fundamental requirements to act as an *aide memoire.*

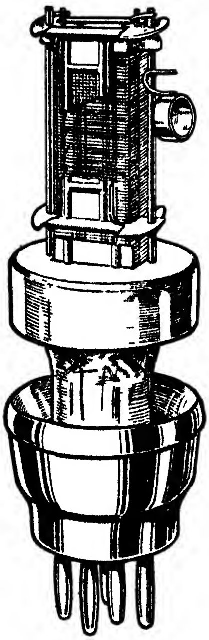


FIG. 18.
ELECTRODE ASSEMBLY OF A MAZDA MAINS R.F. PENTODE.

Radio-frequncy Amplification.—The purpose of the radio-frequency amplifier is to amplify the received signal before detection; it performs two major functions (i) to amplify a weak signal so that the signal fed to the detector may be strong enough for it to function in an efficient manner, free from unreasonable distortion and (ii) to offer opportunities for greater selectivity.

Detection.—The purpose of the detector is to remove the audio-frequency component from the radio-frequency carrier and to perform this office with a minimum of distortion.

Audio-frequency Amplification and Output.—To amplify the audio-frequency output of the detector to the level required for operating the loudspeaker which, it should be noted, is a power operated device and not a voltage

operated device like a valve. This amplification must be performed with minimum distortion.

It is clear that the main purpose of the radio-frequency amplifier is to increase signal strength at radio frequency as much as possible and provide maximum selectivity, the latter with due regard to the necessity for preserving the higher audio frequencies which would be attenuated if the selectivity response curve was triangular rather than square in shape. It is perhaps unfortunate that the conditions necessary for maximum amplification are opposed to those required for maximum selectivity, but in practice, compromise can be effected on favourable terms since really high amplification is not possible where questions of economy have to influence construction and ready interchangeability of valves is essential. The basic circuit of a radio-frequency amplifier is shown at Fig. 19. It will be seen that the valve impedance and anode load are in series and since it is obvious that the amplification factor of the valve will be a dominant factor, the stage gain is expressed by the following very simple equation :—

$$\text{Stage gain} = \frac{\mu \times R}{R + r_a}$$

When μ is the amplification factor of the valve, R is the *dynamic resistance of the anode load and r_a is the valve impedance at working anode, screen and grid voltage.

Stage Gain

To illustrate this simple equation by an example, a screened pentode having an impedance of 700,000 ohms and an amplification factor of 1,200 under operating conditions of anode, screen and grid voltage and assuming a dynamic resistance of 100,000 ohms, will give a gain for the stage as a whole of 150 times. As already expressed in this chapter this elementary mathematics is introduced for its explanatory value and not because it is anticipated that the reader will wish to be involved in such calculations, particularly as the value of dynamic resistance is not readily obtained. Dynamic resistance can be defined as the impedance of a tuned circuit at resonance and increases as losses decrease, the most significant sources of loss usually being high frequency resistance and circuit damping. It might be

* Dynamic resistance = impedance of the tuned circuit at resonance.

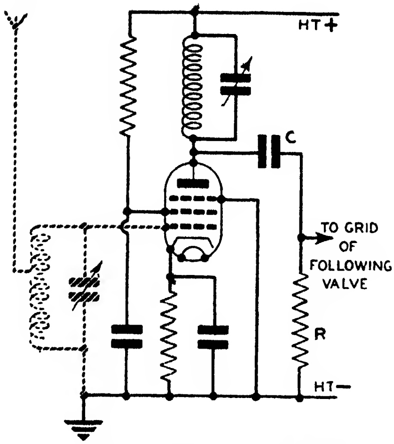


FIG. 19.—BASIC CIRCUIT OF A RADIO-FREQUENCY AMPLIFIER EMPLOYING A RADIO-FREQUENCY PENTODE.

thought that the dynamic resistance could be obtained from the manufacturer of the coil to be used, but this figure will not hold good when the coil is put to practical use since it will be considerably reduced if it precedes a normal type of detector and somewhat increased if it precedes another radio-frequency amplifier, due to feed-back via the interelectrode capacity of the following valve.

It is interesting to take a short cut to the evaluation of stage gain; reference to the above simple equation will show that three factors are involved, amplification factor and impedance of the valve and the effective dynamic resistance of the tuned circuit. With a modern radio-frequency pentode the dynamic resistance is usually small compared to the impedance of the valve and since slope takes care of both amplification factor and impedance, approximate stage gain can be determined by multiplying the dynamic resistance by slope, thus :—

$$\text{Approx. Stage gain} = \text{Slope} \times \text{Dynamic resistance}$$

For the above formula to hold good, dynamic resistance must be in ohms and slope in amps per volt. As intimated earlier, the stage gain practicable is limited by the interelectrode capacity and screening between grid and anode circuits; with good screening, however, and normal sized coils and screening cans instability will not usually be experienced except when two or more stages are used.

Tuned Anode

It is now possible to consider what practical form the anode load may take; the simplest possible arrangement is shown at Fig. 19, the anode load taking the form of a plain tuned anode. The grid circuit is shown dotted as it has nothing in common

with the valve and could in fact be replaced by a resistor, were it not for the influence of feed back, without affecting the stage gain of the valve although the gain of the receiver as a whole would be adversely affected as the magnification of the tuned aerial circuit would be lost, to say nothing of its contribution to selectivity. It is well worth labouring the point that the actual performance of a valve is almost entirely controlled by its anode circuit and *not* its grid circuit. When enthusiasts gather together one hears individuals seeking advice on what values should go in *front* of this or that valve for maximum amplification. It may be safely assumed that such individuals are displaying lamentable ignorance unless some very peculiar factor is involved.

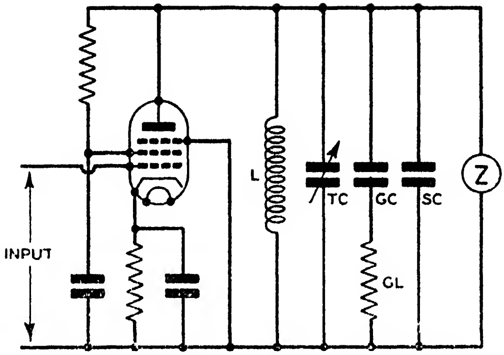


FIG. 20.—A RE-ARRANGEMENT OF FIG. 19 TO ILLUSTRATE THAT THE ANODE LOAD IS SHUNTED BY OTHER COMPONENTS.

L = Tuning inductance, TC — Tuning Capacitor, GC = Grid Capacitor, GL = Grid Leak, SC — Stray Capacity, Z = Input impedance of following valve.

The tuned anode gives limited scope for high selectivity, tends towards additional instability problems and is inconvenient when a ganged capacitor is used since both sides of the capacitor are at H.T. + ; true, this difficulty can be overcome by the often suggested arrangement shown at Fig. 21, but this method invites radio-frequency currents to wander round the H.T. arrangements as a whole which is to be

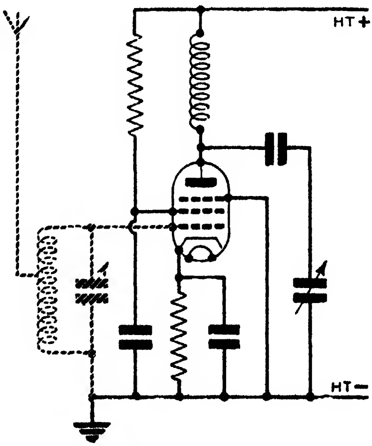


FIG. 21.—A VARIANT OF FIG. 19 ARRANGED SO THAT ONE SIDE OF THE ANODE TUNING CONDENSER IS EARTHED.

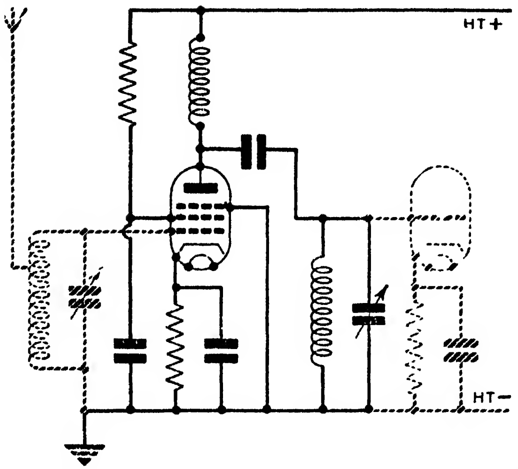


FIG. 22.—AN ALTERNATIVE ARRANGEMENT TO THAT SHOWN AT FIG. 19 IN WHICH THE TUNED CIRCUIT IS PLACED BETWEEN ANODE AND THE EARTH LINE.

shunned by all but the more daring. Fig. 19 will serve to illustrate another consideration which is so often overlooked, which is exactly what the anode circuit comprises. Obviously, it comprises the tuned anode coil with the tuning capacitor in parallel but to this must be added the grid capacitor and grid leak in series, the capacity of the grid-to-all-other-electrodes in the following valve and the grid cathode impedance of the following valve. An attempt to illustrate these unseen factors is made at Fig. 20, where the liberty has been taken of combining H.T. + and H.T. - since these are virtually at the same potential from the radio frequency point of view, however different they may be from the D.C. point of view. Before leaving Fig. 19 to consider alternative arrangements, it may be usefully mentioned that the sole function of the capacitor C, is to prevent the H.T. voltage from reaching the grid of the following valve, and the resistor R is merely a convenient means of applying grid bias to it. These remarks regarding C and R only apply if the following valve is another radio-frequency amplifier. If the following valve is a detector, additional considerations may be paramount.

Tuned Grid Coupling

Perhaps the circuit most commonly used by the experimenter is the tuned grid coupling as shown at Fig. 22. It is the radio-frequency equivalent of the tuned anode with the exception that the tuned circuit is in parallel with a radio-frequency choke; the effective dynamic resistance is somewhat reduced, but a corresponding gain in stability and convenience results. It will

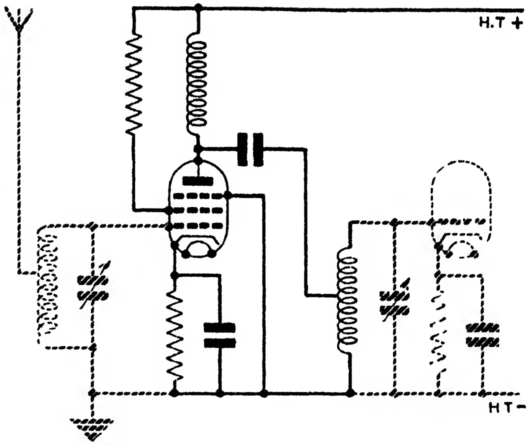


FIG. 23.—A VARIANT OF FIG. 22 SHOWING HOW THE ANODE LOAD CAN BE VARIED BY TAPPING THE TUNING INDUCTANCE.

be noted that this circuit has two practical advantages, namely that one side of the tuning capacitor being at earth potential, the grid leak is rendered redundant since the grid circuit for bias purposes is completed through the inductance. The inductance may be turned into an auto-transformer by taking the coupling capacitor to a tap on the coil as shown in the illustration in Fig. 23; such a course may be justified on the grounds of selectivity or in the case of multi-stage radio amplifiers be imperative to obtain stability; the lower the tapping is placed, the less will be the stage gain as the increase due to the step up ratio of the transformer will be more than offset by the fall of gain developed by the actual valve, consequent upon the reduction of the effective dynamic resistance of the anode load.

In fact, the condition of maximum possible gain, especially when the following valve is the detector, is sometimes obtained by tapping the grid of the following valve a short way down the inductance. The loss of gain resulting from less than the entire potential difference across the inductance is again more than offset by the increase of amplification consequent upon a rise of dynamic resistance of the tuned circuit due to the coil being relieved of part of the damping of the following valve. The critical tapping point is often determined by experiment in which case it is necessary to obtain specimens of the valves to be used which will give the highest gain and inter-electrode capacity otherwise trouble may be expected when valve replacement becomes necessary.

Tuned grid coupling lends itself to modification to bandpass coupling and such an arrangement is not uncommon in high

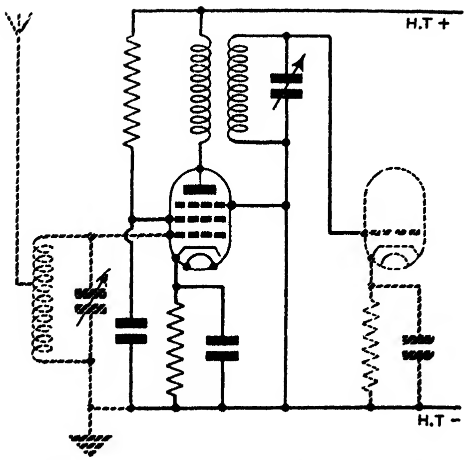


FIG. 24.—IN THIS CIRCUIT A TRANSFORMER FORMS THE ANODE LOAD.

quality multi-stage radio-frequency amplifiers which sometimes employ a combination of band-pass and sharply tuned single circuits to obtain the desired type of over-all response curve.

Tuned Transformer

Perhaps the best of all radio-frequency inter-valve couplings is the tuned transformer, the circuit of which is shown at Fig. 24. This arrangement has many advantages, the ratio can be adjusted by varying the number of primary turns assuming that the secondary is tuned and the coupling between primary and secondary can be varied by the space between the windings or their angular relationship. This permits of not only ease of effecting compromises between gain and selectivity but permits the shape of the response curve to be influenced to a very great extent. Other important advantages are that one side of the tuning capacitor is at earth potential and both sides are at earth potential from the D.C. point of view ; variable capacitors which have one or both sides at a high D.C. potential relative to their main framework can be a source of noise when insulators become dirty. Yet another and very important advantage is the complete metallic isolation of primary and secondary which precludes mains hum from reaching the grid from the anode supply of the preceding valve or the grid being driven positive due to a leaky coupling capacitor, although this latter advantage is shared by the tuned grid. The illustration, Fig. 24, shows the secondary as the tuned circuit. It is, however, perfectly feasible to tune the primary but certain practical advantages are thereby lost and the tendency to instability somewhat increased ; where a special form of response curve is required from the coupling it is possible to tune both primary and secondary but usually a bandpass tuned grid will be preferred owing to the greater ease

of employing mixed capacity and inductive coupling to give constant band-width over the whole swing of the tuning capacitor.

There is little limit to the number of different ways that a radio-frequency coupling can be arranged, but sufficient have been described to give an insight into the working of the screened radio-frequency amplifying valve, its peculiarities and the considerations governing its construction and use and also to emphasize that the valve and its anode coupling are part of a team and cannot be considered independently.

The Variable MU Characteristic

It is obvious that some form of volume control must be fitted to every receiver and it is very desirable that this control should be effected in the radio-frequency amplifier and various possible means of accomplishing this end have been devised. Since, however, the greatest reduction will be required on the largest signal, this control must be exercised in such a manner that the first valve is not overloaded. The method in general use is variation of the gain of the radio-frequency amplifier valve by increasing its grid bias which would bring about disastrous results in a valve with a grid characteristic such as that shown at Fig. 9 since an increase of bias would force the incoming signal on to a part of the curve which exhibits serious curvature, or on to the cutoff point. In practice a special form of radio-frequency tetrode or pentode is used, known as the variable mu type which has a modified grid-volts/anode-current curve a typical example of which is shown at Fig. 25. It will be observed from this

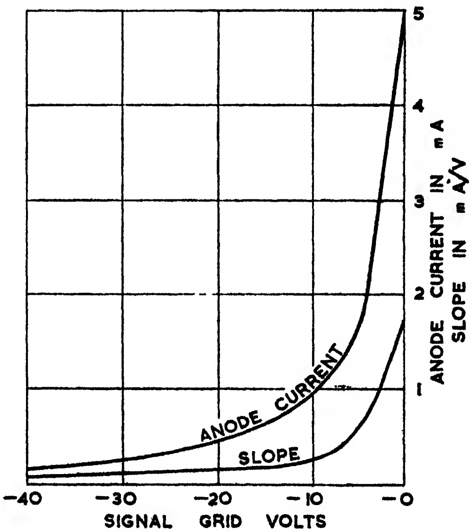


FIG. 25.—THE EFFECT OF GRID VOLTAGE ON THE ANODE CURRENT AND SLOPE OF A VARIABLE-MU VALVE.

illustration that the long sweeping curve permits a fairly large input to be accepted without the employed portion of the curve exhibiting very serious curvature and that a very large value of grid bias can be applied without running a relatively large input to cutoff.

The same illustration shows the relationship of slope or mutual conductance and grid voltage from which it may be observed that control is exercised from maximum to virtual zero which means that control can be exercised beyond the point where stage gain is unity and stage loss takes its place. When manual control is to be employed it is usual to place a variable resistor and the normal bias resistor in series, but it is inconvenient to obtain a really large grid voltage in this way since the increase of bias brings about a decrease in anode current, and it follows that a very large value variable resistor is necessary to produce a high bias voltage. A high value of variable bias resistor is undesirable for various reasons and one means of overcoming the difficulty is to put a suitable resistor between H.T. + and the cathode end of the variable resistor so that a reasonable value of current is always flowing through it.

As will be seen later the gain of a variable mu valve is varied automatically in the more elaborate types of receiver by employing a diode valve to exercise control.

The variable mu characteristic is brought about by the geometry of the control grid which is sometimes wound so that the spacing between each adjacent turn increases progressively from one end of the grid to the other, alternatively, the special characteristic is achieved by merely removing a few turns from a normally wound grid at a selected point or points, see Fig. 15.

THE FREQUENCY CHANGER

The reader who has already had some acquaintance with the construction of radio receivers employing one or more radio-frequency stages, will be only too well aware of the practical difficulties of persuading the numerous tuned circuits to line up properly at all points of the tuning range and, even when and if these difficulties are overcome and adequate stability achieved, both selectivity and amplification may have been found disappointing. Many of these difficulties have been wholely or

largely overcome by the use of the superheterodyne, the principle of which is dealt with in Chapter XIV. The very centre of the superheterodyne is the frequency changer stage or oscillator and mixer stage, as it is sometimes called. The prime function of the frequency changer stage is, as its name implies, to change the frequency of the incoming signal to that of the pre-tuned intermediate frequency amplifier, but as is so often the case, definition of a broad principle is far from being the full story and it will be desirable, therefore, to define more precisely the function of this stage. The frequency changer is required to perform its task in a manner that fulfills the following conditions as completely as may be possible or economically practicable. (*a*) Conversion conductance shall be as high as possible. (*b*) Signal to noise ratio shall be as favourable as possible. (*c*) The amplitude of oscillator harmonics shall be as small as possible. (*d*) Envelope distortion must be as small as possible. (*e*) Any possibility of cross modulation in either frequency changer (or pre-amplifier, if one is used) must be avoided at all costs.

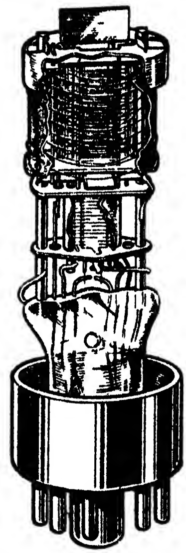


FIG. 26.—ELECTRODE ASSEMBLY OF THE MAZDA TH41.
A mains triode heptode.

It may seem that there is an omission from the above list of requirements, namely that hum must be excluded from reaching the grid from the anode circuit of the preamplifier, if one is used, but this is not so serious as it might at first sight appear in this stage as hum would cause frequency modulation as distinct from amplitude modulation to which the ultimate detector will not be responsive. The problem now being clearly defined, attention can be turned to special valves normally used as frequency changers.

The Triode Hexode

The commonest form of frequency changer valve is the triode heptode comprising two valves enclosed in a single glass bulb, one being a triode intended to perform the function of a local

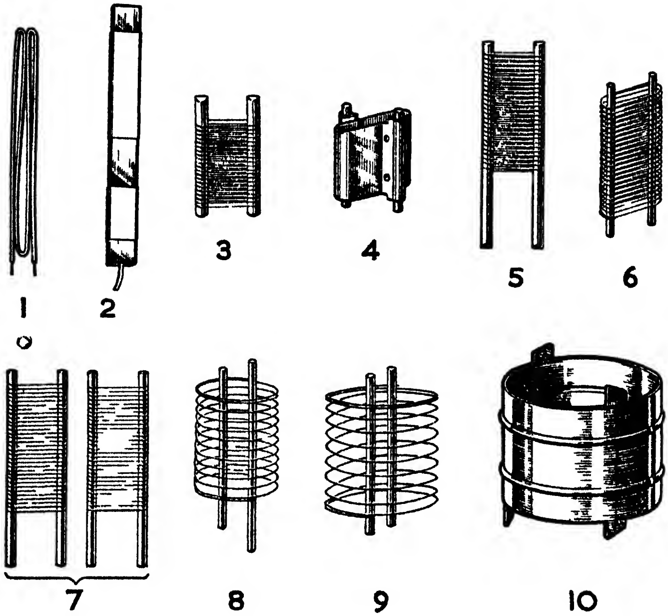


FIG. 27—THE ELECTRODES OF THE MAZDA TH41

Numbers correspond with the symbol diagram at Fig. 28, which identifies the purpose of each electrode.

oscillator and the other a heptode which is an electrode assembly consisting of cathode, anode and five grids, two grids being connected together to form a screen. Fig. 26 shows the electrode assembly of a typical triode heptode while Fig. 27 shows an exploded view of the various electrodes. The heptode is really a pentode with an additional control grid which is screened both from the anode and normal control grid. The heptode is also available in a form known as a hexode which differs by having no suppressor grid between screen and anode, giving the valve tetrode instead of pentode characteristics; unfortunately, the words hexode and heptode have become mixed, as at least one valve manufacturer, realizing the advantage of the pentode characteristics, modified the hexode to include a suppressor grid, but considered it unnecessary or undesirable to alter the nomenclature of the valve. Fig. 28 shows the symbol of a triode heptode showing the function of the various electrodes, the small numbers relate to the numerical annotation at Fig. 27, permitting

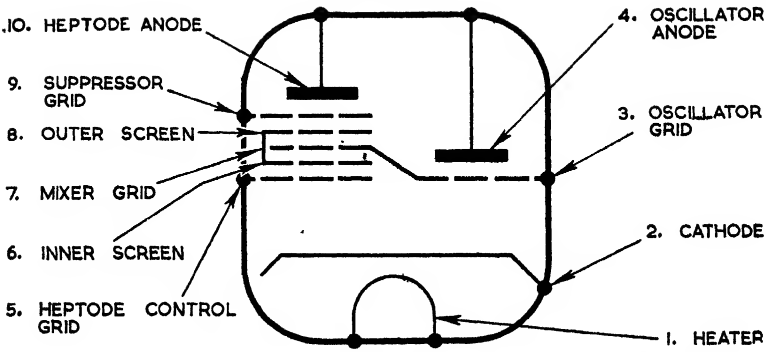


FIG. 28.—THE USUAL SYMBOL OF A TRIODE HEPTODE CROSS REFERENCED WITH FIG. 27.

Showing the physical appearance of each electrode.

the symbolization, function and physical appearance of each electrode to be co-ordinated. Other types of frequency changer are in use or are not yet considered obsolete while special arrangements are usually considered desirable for efficient operation at ultra high frequencies. The system of explanation adopted, however, will be to analyse the triode hexode critically, the requirements of which are largely typical and then to comment on the alternatives. These remarks are equally true of the triode heptode.

The prime purpose of the frequency changer is to heterodyne the incoming signal or, put another way, to mix the incoming signal with a locally generated oscillation, so that an output is produced which is in effect a new and fixed carrier frequency bearing the same modulation as the incoming signal. This mixing produces in fact two new modulated frequencies, being the sum and difference between the incoming and local oscillator frequencies, but unfortunately numerous other frequencies are also present. A tuned circuit is placed as an anode load to select the wanted frequency which is termed the intermediate frequency and which remains constant irrespective of the frequency of the incoming signal, thus premitting further amplification by a pre-tuned amplifier of fixed frequency which will always work at maximum efficiency and at a constant bandwidth. The advantages of this arrangement and certain fundamental principles are dealt with elsewhere, and these brief remarks are intended merely to place the frequency changer in its proper

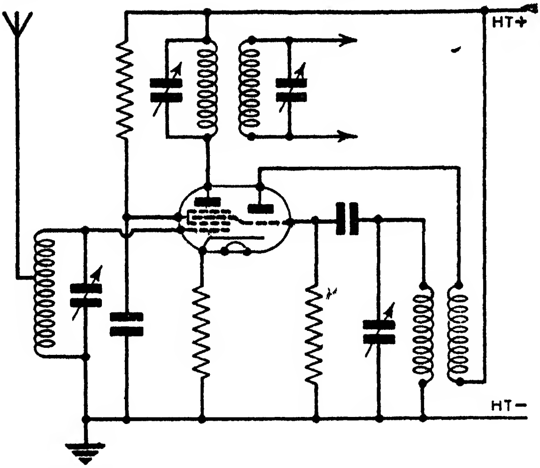


FIG. 29.—THE TRIODE HEXODE ARRANGED AS A FREQUENCY CHANGER.

perspective before dealing with the finer points of the actual valve, its functioning and requirements.

The Hexode Section

The operation of the hexode portion of the valve is relatively straightforward and a typical circuit is shown at Fig. 29. The cathode provides a stream of electrons which reaches the anode through the several grids and which is varied by the instantaneous voltage on both the signal grid and oscillator grid, producing a varying anode current the waveform of which is influenced by both the signal and oscillator inputs. The efficiency of conversion is measured by noting the change of anode current at the selected intermediate frequency against the voltage change of the signal grid. This relationship is known as the *conversion conductance* and is expressed as milliamps. per volt. That is to say if a change of one volt on the signal grid brings about a change of one milliamp. in the intermediate frequency anode current, then the conversion conductance would be 1 milliamp. per volt. The oscillator grid of the hexode section is internally connected to the oscillator grid of the triode, but nevertheless the amplitude of the locally generated oscillation is controlled by outside sources,

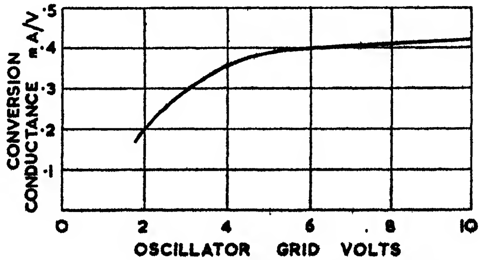


FIG. 30.—THE EFFECT OF OSCILLATOR GRID VOLTAGE ON THE TRIODE HEXODE FREQUENCY CHANGER.

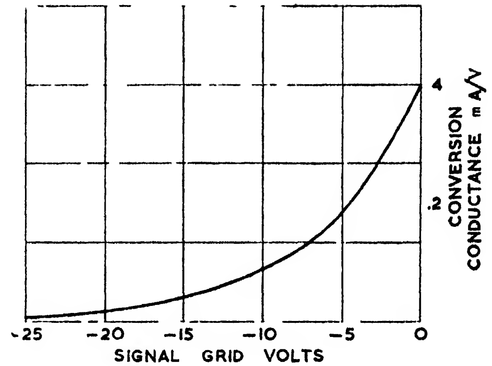


FIG. 31.—THE EFFECT OF SIGNAL GRID VOLTAGE ON THE EFFICIENCY OF A TRIODE HEXODE, THE HEXODE PORTION OF WHICH HAS A VARIABLE-MU CHARACTERISTIC.

usually by the tightness of coupling between the oscillator anode and grid coils. Since this voltage will be one of the two controlling factors of the electron stream it might be expected that its amplitude will influence conversion conductance; and reference to Fig. 30 will show that this is actually the case. This curve shows the direct relationship between oscillator grid volts plotted against conversion conductance; it will be seen that in the example used, conversion conductance increases rapidly as the oscillator grid voltage is increased up to 6 volts and thereafter remains sensibly constant. The optimum figure lies somewhere between 5 and 7 volts according to a number of circumstances, since two conditions must be fulfilled. The oscillator voltage must not drop much below 6 volts at any point of the tuning range, a requirement that is by no means easy to arrange particularly on short wavebands, conversely heterodyne volts should not be allowed to exceed greatly the optimum value as such an increase will increase the nuisance value of oscillator harmonics.

Grid Construction

Since it is essential that cross modulation shall not take place the grid is of variable mu construction, the advantages of which have already been explained, and since conversion conductance is more interesting than mere slope the conventional grid-volts/anode-current curve is not shown, its place being taken by a signal-grid-volts/conversion-conductance curve which is shown in Fig. 31 the very gradual control of conversion conductance which is in effect stage gain, is apparent; normally such control will be exercised automatically in the form of automatic volume control which is described later. It is however, highly debatable

to what extent control shall be exercised in this stage as reduction of gain will bring about a greater reduction of the wanted signal than of noise generated by the valve, while on the other hand overloading is quite unpermissible owing to the danger of cross modulation and envelope distortion; it is, therefore, sometimes considered desirable in the more elaborate type of set not only to limit the amount of automatic control exercised on this stage but to vary this limitation on different wavebands.

Bias Resistance

The value of the bias resistor shown at Fig. 29 must be the subject of special comment. On medium and long waves the value chosen is the usual compromise between maximum gain and avoidance of grid current, but when working on the higher frequency bands a higher value is desirable and sometimes essential. A small interelectrode capacity exists between the signal and oscillator grid in spite of the screen grid placed between them, on medium and long waves the frequencies on the two grids are very dissimilar and the effect of this minute capacity is extremely small. Any voltage which may appear on the signal grid due to this coupling can be ignored, but when the receiver is tuned to a high-frequency band, sufficient oscillator voltage may appear on the signal grid to drive this grid into grid current and cause serious damping of the preceding tuned circuit and partial rectification with its attendant dangers. This unfortunate coupling makes it imperative to chose a value of bias resistor which will prevent the valve from going into grid current even at the expense of conversion conductance, the increase will of course depend on the highest frequency to which the receiver will tune but as a very general guide, the optimum value is doubled on most standard receivers tuning down to say 20 megacycles; some receivers go so far as to use a contact on the wave-change switch to add additional bias resistance for the short waveband.

The Triode Section

Little need be said about the triode section which in the arrangement at Fig. 29 is a very conventional oscillator, the required constant output irrespective of frequency being largely controlled by the coupling coils and anode voltage; when the very best

performance is required on the higher frequency wavebands it is usually desirable to employ a separate oscillator valve to give greater scope for avoiding frequency drag, that is the tendency for variations of signal frequency tuning to influence the oscillator frequency. Such arrangements are outside the scope of this book and are commonly found in works devoted solely to the needs of specialised shortwave reception. Among American valves numerous examples will be found of hexodes, without the attendant triode, intended for use as frequency changers with a separate oscillator valve (not necessarily a triode) or for

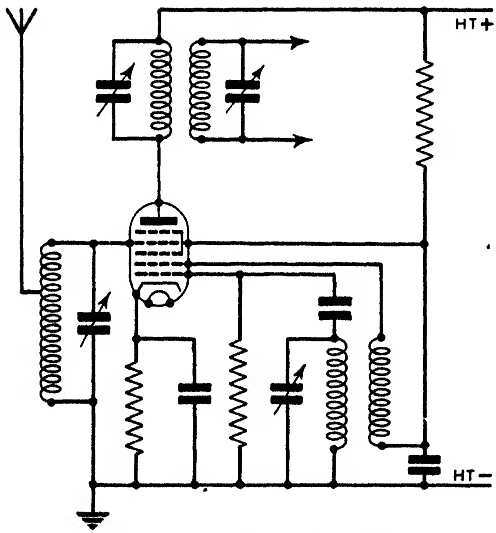


FIG. 32.—A PENTAGRID ARRANGED AS A FREQUENCY CHANGER.

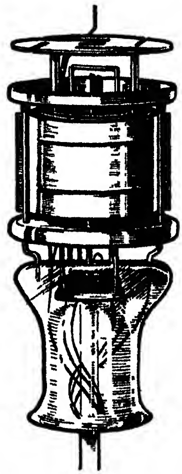


FIG. 33.—THE ELECTRODE ASSEMBLY OF A PENTAGRID TYPE VALVE. The example chosen for illustration is the Mullard FC2A which is designated an octode because it has a suppressor grid.

use in other spheres where the mixing of two independent frequencies is required.

The Pentagrid

Another interesting form of frequency changer is the pentagrid, the basic circuit of which is shown at Fig. 32, in addition to

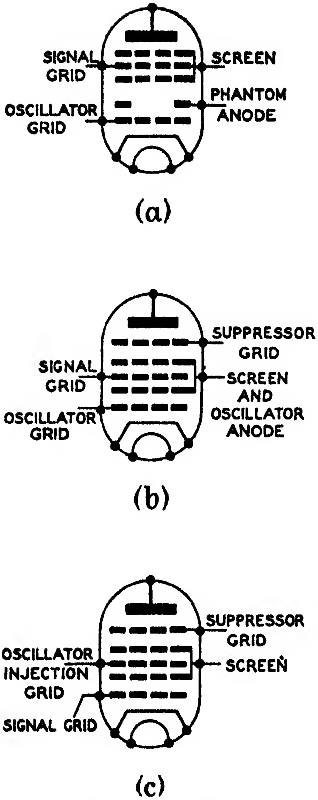


FIG. 34.—THREE ESSENTIALLY DIFFERENT VALVES BUT ALL CALLED PENTAGRIDS.

the usual cathode, heater and anode it has five grids which reading outwards from the cathode are oscillator grid, oscillator anode, screen grid, signal grid and screen grid, all of which are conventional except the grid designated as the oscillator anode which is in effect a pair of vertical rods and by virtue of its insignificant dimensions is often called the phantom anode. The manner in which this valve functions is interesting. The cathode oscillator grid and phantom anode are arranged to oscillate in the usual way, see Fig. 32. This little assembly can be envisaged as a cathode which supplies the electron stream to the rest of the valve; the density of the available stream varies at the oscillator frequency. This stream is again controlled by the signal grid and thus the anode current varies sympathetically with the oscillator frequency and the signal frequency.

Pentagrid frequency changer valves of the type depicted at Fig. 33 are very satisfactory on medium and long waves, but on short waves they become progressively less efficient as frequency increases; this drop in efficiency is due to the difficulty of maintaining oscillator amplitude at the higher frequencies and highly undesirable inter-action between the oscillator and signal grids, the most undesirable of which is the detuning of the oscillator by changes of signal grid voltage which, it will be realized, may be due to both the incoming signal and the action of automatic volume control.

To overcome the serious shortcomings of the pentagrid described above there is another type of pentagrid which uses a very different form of construction; it is very regrettable that these two valves should both be called pentagrids as it

is impossible to distinguish the one from the other without consulting the valve base connections. Briefly, this variant, of which the 6SA7 is typical, has no phantom anode and uses the inner screen grid to perform the additional function of anode of the triode oscillator otherwise the valve is generally similar except that a suppressor grid is interposed between the outer screen grid and the anode. This arrangement gets round the disadvantages of the type of pentagrid first described at a small cost in conversion conductance.

There is yet another form of pentagrid of American origin, such as the 6L7, but fortunately it is distinguished from other pentagrids by being called a pentagrid mixer ; it is in all respects similar to the second type of pentagrid described above but is intended for use with a separate oscillator, the grid nearest the cathode being used as the signal grid and the outer grid for injecting the oscillator output delivered by the separate oscillator. To clarify these three different forms of pentagrid they are shown as block diagrams at Fig. 34, the numerical order of their presentation being the same as the order used in the above explanation.

The Triode Pentode

Fig. 35 shows a triode pentode frequency changer and irrespective of whether the two electrode assemblies are housed in one envelope or are separate valves the system is different from either hexode, heptode or pentagrid. The pentode is arranged with an anode load consisting of an intermediate frequency tuned circuit. The triode section may seem a little unusual as the anode is coupled to the cathode instead of the grid, the reason

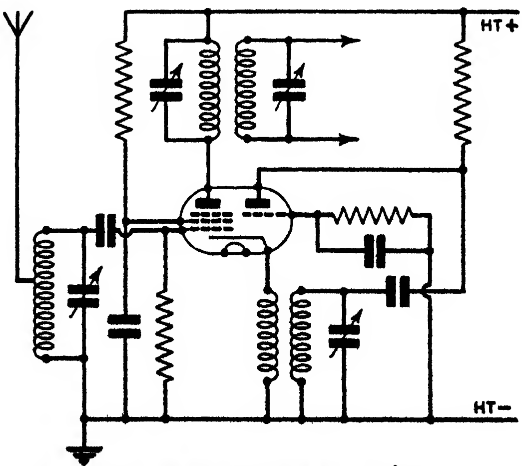


Fig. 35.—A Triode Pentode arranged as a Frequency Changer.

for this departure from common practice is so that the potential of some electrode that is common to both pentode and triode can be varied which, in the present arrangement is the cathode. If separate valves are used the cathodes are joined together and taken to earth through the cathode inductance. In this way the anode current of the pentode will be controlled by both the oscillator and the incoming signal. The oscillator coupling between anode and cathode needs some explanation. The behaviour of a valve is usually controlled by imposing a potential difference between grid and cathode, normally the cathode is held at a fixed potential and the grid is varied ; in the arrangement under review the oscillator is held at a fixed potential and the cathode is varied, thus the condition is fulfilled whereby the potential between grid and cathode is varied, it makes little difference whether grid or cathode are used as the variable element except that it is usually desirable to hold the cathode at earth potential from the radio frequency point of view which is, of course, impossible if the cathode is to be used as a radio-frequency control electrode.

Those who already have some knowledge of the frequency changing stage may feel slightly surprised that no reference has been made to the frequency changer being a detector ; in very early forms the frequency changer was invariably a straightforward detector arranged either as a self-oscillator or coupled to a separate oscillator, and although contemporary text books still refer to rectification as an essential condition for frequency changing it is indeed hard to explain how a variable mu valve biased well outside the region of grid current can rectify, and equally hard to explain why cross modulation should be absent if detection is present. It is hoped that readers will find the approach adopted readily understandable and adequate.

DETECTION

The function of the detector is to separate the modulation from the carrier. It will be recalled that the raw material which is picked up by the aerial consists of the carrier wave, the amplitude of which varies in sympathy with the audio-frequency programme material being transmitted. Although the question of modulation is referred to elsewhere it will be well to refresh the memory and for this purpose Fig. 36 is included which shows

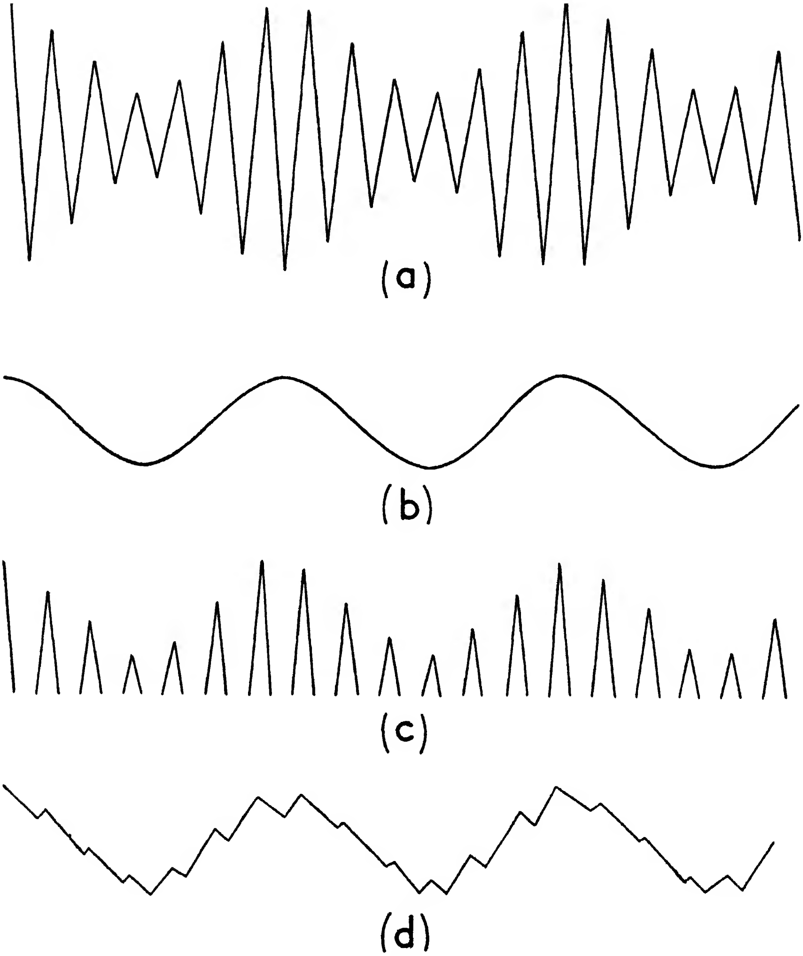


FIG. 36.—A DIAGRAMMATIC REPRESENTATION OF THE PRINCIPLE OF DETECTION. (*a*) The received waveform. (*b*) The A.F. modulation which it is desired to remove from (*a*). (*c*) The result of rectifying (*a*). (*d*) The elimination of the separate R.F. half-cycles in (*c*) due to the time constant; the jagged appearance of (*d*) is due to the charging and discharging of the time constant capacity.

the received waveform (*a*), and the audio-frequency component (*b*), that it is desired to separate from the carrier. A little thought will show that in order to perform this change it is necessary to cut the received waveform in half horizontally and then to devise a circuit which will be unresponsive to the rapid changes of the carrier frequency but responsive to the slow change of amplitude

caused by modulation; these two processes are shown at (*c*) and (*d*) respectively in the same illustration. The difference between rectification and detection will be apparent, the illustration (*c*) being rectification, and (*d*) detection; in the case being instanced the difference between these two functions is clear-cut but they overlap in certain specialized forms of radio application, notably in radar. There are several fundamentally different ways of detecting a signal, varying from the crystal detector to complicated methods outside the scope of this book, but for all normal purposes diode detection, grid detection, anode bend detection and their more interesting variants will suffice. Although falling into disuse the anode bend detector will be considered first as its functioning is most readily explained.

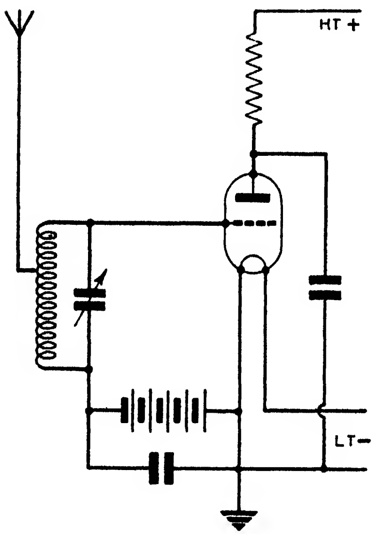


Fig. 37.—Basic Circuit of an Anode Bend Detector.

The Anode Bend Detector

Fig. 37 shows the basic circuit of an anode bend detector; it will be observed that the grid is biased negative in respect to the cathode, the value chosen is critical and should bias the valve to a point where the flow of anode current almost ceases and where further decrease can only be obtained with an unreasonable increase of negative voltage. With the valve biased in this way, the negative swing of the incoming signal will not bring about any worthwhile change as it only adds to the negative voltage already imposed on the grid; the positive swing on the other hand will increase the anode current to a more or less proportional extent. The qualification "more or less" is due to the fact that the increasing input voltage must first of all surmount a curved portion of the characteristic before reaching the straight portion, it is apparent therefore that distortion on weak signals will be more severe than on strong signals. The general mechanics of this process is shown at Fig. 38 which in

the interest of clarity ignores distortion due to non-linearity of the valve characteristic. Perusal of this illustration will show that rectification has occurred instead of detection; this is because the presence of capacity has been deliberately ignored in this illustration. Reference to Fig. 37 will show that a capacitor is connected across the anode load, which should normally be very high, usually upwards of 100,000 ohms, this capacitor will act as a reservoir and will begin to discharge when anode voltage falls and charge when the anode voltage rises; if the value of the capacitor is sufficiently high, discharge cannot occur fast enough to follow the rapid radio-frequency variations but providing it is not too high it can follow the very much slower audio-frequency variations, thus the output will resemble the waveform shown at (*d*) in Fig. 36. It is obvious that the lazy action of the anode capacitor will introduce some distortion by curtailing the rise and fall of audio-frequency current and will also introduce some attenuation of the higher audio-frequencies which may or may not be desirable.

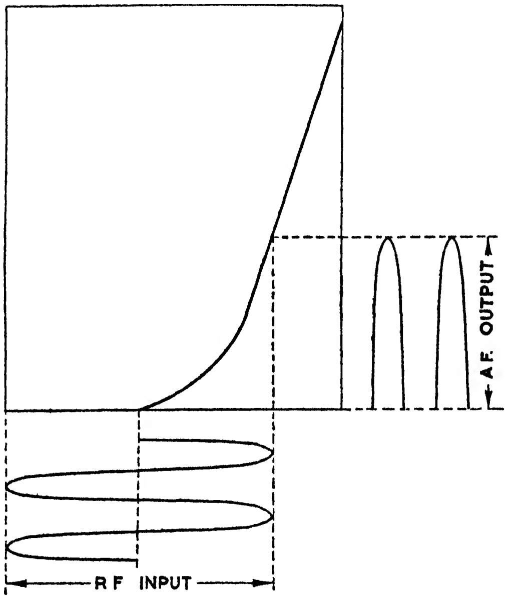


FIG. 38.—HOW THE ANODE BEND DETECTOR FUNCTIONS.

Distortion due to valve curvature has been ignored in this illustration.

In actual fact an anode bend detector will function, although somewhat indifferently, without a capacitor across the anode load owing to the existence of incidental capacity between the anode circuit and other objects; it is apparent, therefore, that the output waveform shown at Fig. 38 is purely diagrammatic and that detection and not rectification must result. In the explanation of detection that has so far been unfolded, mention

of a point has been deferred until this moment in order to avoid too many conflicting issues at the same time. All the waveforms shown at Fig. 36 show the audio-frequency component at the same amplitude, obviously forms of detection which amplify should be represented by the audio-frequency component at (*b*), (*c*), and (*d*) having greater amplitude than (*a*), while in non-amplifying forms the reverse should be the case since such detectors do not function at 100 per cent. efficiency.

Many contemporaries prefer to regard detection and rectification as one and the same thing but in the interest of clarity of explanation, the word rectification is used here as meaning the conversion of alternating to direct current or voltage and the word detection is reserved for the special form of rectification where it is desired to preserve some particular characteristic after rectification, which for the present purpose is the audio-frequency component.

It is significant that the custom of using indirectly heated valves for illustration has been varied at Fig. 37 ; this is because the ordinary method of biasing by a resistor in the cathode circuit is not very satisfactory as it is imperative that the bias is held constant even with very low anode current. It was not desired to confuse the explanation of the principle by introducing unusual bias arrangements, but it may be noted that the difficulty is usually overcome by taking negative voltage from a resistor in the common H.T. − line or by using the normal bias resistor and connecting a high value resistor between cathode and H.T. + of such a value that a few milliamps. flow through the bias resistor unaffected by the behaviour of the valve.

The advantage of the anode bend detector is the fact that no grid current flows and therefore the working grid-cathode impedance is very high and the preceding tuned circuit is therefore relieved of the relatively heavy damping caused by other detectors. The damping imposed by this type of detector is little more than that due to losses in the valve base and holder which can be ignored in normal circumstances. Another advantage is that the gain of this type of detector is considerable. The disadvantages may be summarized as lack of linearity particularly with small inputs which cause distortion and accentuated fading since the distortion takes the form of a small gain for a small input and a larger gain for a large input which obviously accentuates any fading which may be present. This latter

disadvantage can, however, be somewhat offset by using a pentode valve, the screening grid being connected to H.T. + through a very high value resistor, usually between two and three megohms. With this arrangement the resistor, which is sometimes placed between the screening grid and cathode or earth, must be omitted.

The anode bend detector is variously known in America as high level plate detector, grid bias detector, and class C detector.

The Diode Detector

Attention can now be directed to the diode detector which performs this necessary function without any amplification from the valve whatsoever. The function of the diode detector is extremely simple and relies on the fact that the diode will only pass current when the anode is positive with respect to cathode, consequently, if a signal voltage is applied in the manner shown at Fig. 39 the diode will pass current when the applied radio-frequency voltage swings the anode positive in respect to the cathode and no current will flow on the other half-cycle; the radio-frequency waveform is therefore cut in half horizontally leaving a voltage variation across the diode load as shown at (*c*) Fig. 36. To convert this half envelope to a pure audio-frequency variation, it is merely necessary to connect a capacitor across the diode load as shown in Fig. 39, in order to oppose what would otherwise be the rapid changes of voltage due to the radio frequency, in exactly the same manner as already described in connection with the anode bend detector. The average diode detector can be used with an anode load of the order of 0·5 megohm and therefore the value of the attendant capacitor must be restricted if high note attenuation is to be kept within acceptable limits; when used to detect radio-frequency input the value chosen is usually from 100 to 200 p.f., but when following an intermediate frequency amplifier the value is sometimes increased up to 500 p.f. Fig. 40 gives the characteristic of a diode with an anode load of 0·5 megohm, it will be seen

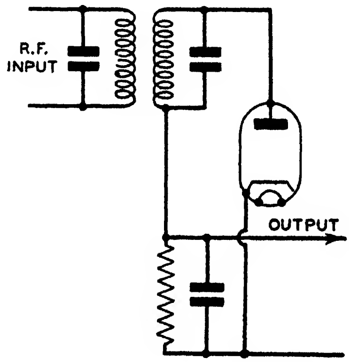


FIG. 39.—A TYPICAL DIODE DETECTOR CIRCUIT.

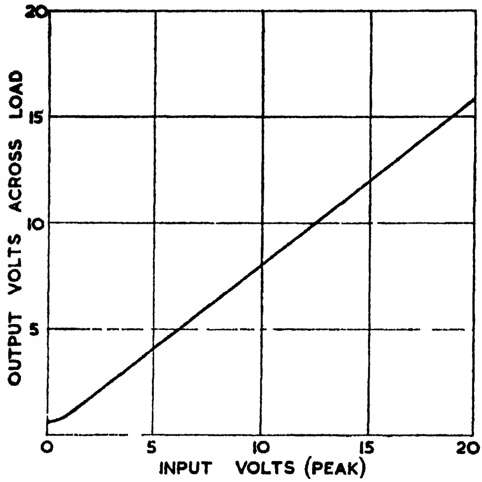


FIG. 40.—THE RELATIONSHIP BETWEEN INPUT AND RECTIFIED OUTPUT OF A DIODE DETECTOR. Note that the gain is less than unity.

that absolute linearity is maintained except for a very small input; it will also be noted that, as explained earlier, anode current starts to flow when the applied potential is just negative in respect to the cathode; this, in effect, causes it to clip the incoming waveform slightly, but the distortion thereby caused is only significant with very small input which illustrates very clearly the need for some form of amplification before detection, except when receiving powerful signals such as those experienced from a nearby transmitter.

The outstanding disadvantage of the diode detector is the adverse effect that it has on the tuned circuit across which it is connected. However the diode is arranged, it acts like a resistor across the tuned circuit and has the effect on it of flattening its response curve, reducing output and decreasing selectivity. This factor must be borne in mind when interpreting Fig. 40, since, when examining the output to be expected from a given input, it should be realized that this input will be reduced by the mere presence of the diode. The damping effect of a diode may be assumed, for practical purposes, to be equal to the damping that would be caused by a resistor connected across the tuned circuit having a value equal to half that of the diode load resistance thus, if the diode load is 0·5 megohm, then damping may be taken as equal to 0·25 megohm.

The circuit shown at Fig. 39 is only one of many ways of arranging a diode but in all cases the action is the same. The diode is also in common use for other purposes than detection, notably for producing an automatically variable D.C. voltage for controlling the gain of such valves as are employed in front of the detector, a system known as automatic volume control. This application is dealt with immediately

following other forms of detection which are described below and in Chapter XIII.

The Leaky Grid Detector

Another popular detector is the leaky grid detector, otherwise known as the cumulative grid detector, or in America as the grid leak and capacitor detector. Speaking very broadly, the leaky grid detector is a diode with a triode amplifier, a single triode performing both functions, the grid acting as the detector anode as well as the amplifier grid. The precise functioning of this type of detector is not easy to explain, and there are perhaps half a dozen different ways of framing the explanation which may appear to conflict and are most confusing to beginners. It is hoped, however, that the following explanation will prove helpful.

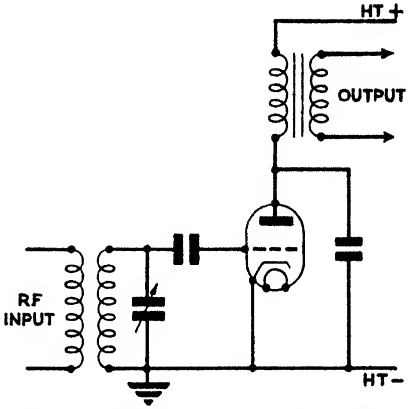


Fig. 41.—Circuit of the Leaky Grid Detector.

With grid leak deliberately omitted to illustrate the text.

Reference to Fig. 41 shows the conventional circuit of a leaky grid detector from which an essential component has been deliberately omitted. The incoming signal will cause the tuned circuit to swing alternatively positive and negative, which means that the grid will also become alternatively positive and negative. When the grid is driven positive, grid current will flow, that is to say electrons will pass from cathode to grid, where they are unable to escape and therefore the grid will become more and more negative with each positive half-cycle,

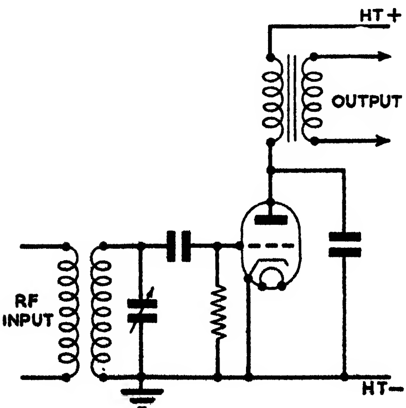


Fig. 42.—Fig. 41 with Grid leak added.

paradoxical though this process may appear. Clearly if this accumulation was allowed to continue it would build up until the incoming signal was no longer able to drive the grid positive. Consider now Fig. 42 which is the same circuit as Fig. 41, but with an additional component, a resistor from grid to cathode. This resistor, if of low value, will obviously prevent the accumulation of electrons on the grid and allow the grid voltage to vary in sympathy with the applied radio frequency voltage. The very essence of the system is dependent on using a selected value of resistor which will produce a condition mid-way between total blockage of the grid and no blockage whatever. In fact, a precisely selected condition whereby the electrons can leak away from the grid at a rate commensurate with the slow change of the audio-frequency envelope, but not fast enough to follow the rapid radio-frequency changes. To summarize, the grid circuit of a leaky grid detector is so arranged that the grid will be driven negative in a manner more or less equal to the amplitude variations of the incoming signal. The qualification, "more or less" is necessary for several reasons chief among which is the non-linearity of the grid current characteristics.

The fact that the action of a leaky grid detector is similar to that of a diode directly coupled to a triode should not be interpreted to mean that the stage gain of the triode, when performing both functions, is the same as would be the case if the triode were used as an independent amplifier. The reason for this limitation is not obvious and is important as it influences receiver design. In the case of a leaky grid detector both radio-frequency and audio-frequency voltages appear on the grid, and the valve will overload if either of these reaches too high a value. It is obvious, therefore, that if the input must be limited so that the radio-frequency input does not cause overload then the audio-frequency voltage will only be half of the permissible input.

In order that grid voltage shall have the largest possible influence over grid current, the anode voltage is normally reduced from the maximum permissible to half or even less, until the required compromise is effected between sensitivity which is improved by lowering the anode voltage and plate circuit linearity and power handling capacity which is improved by increasing the anode voltage. When the last two attributes are

required at the expense of sensitivity, the circuit constants are changed somewhat and become known as a power grid detector; such circuit constants are dependent on a number of factors but 0·0001 mfd. for the grid capacitor and 0·25 megohm for the grid leak are average values with an anode voltage in the neighbourhood of 150 volts or so. It will be realized that although the power grid detector is less sensitive, the average flow of grid current will be higher and consequently the damping on the preceding tuned circuit will also be higher. As an example, with the circuit constants suggested above, the damping imposed will be equivalent to little more than 120,000 ohms which will have really serious effects on both the selectivity and output developed across the preceding tuned circuit.

Infinite Impedance Detection

It is apparent from the summation of the various detector circuits described, that all have the disadvantage of loading the preceding tuned circuit with the exception of the anode bend detector which is seriously deficient regarding quality of reproduction, and attention is therefore now directed to yet another system which is extremely linear and which imposes no damping on the preceding tuned circuit. This arrangement is known as infinite impedance detection since the impedance of the input circuit, i.e., the effective impedance between grid and cathode, is infinitely high; in fact, under certain selected conditions the impedance is negative which means that the output developed across the preceding tuned circuit is actually increased by the presence of this form of detector. The arrangement is shown at Fig. 43 and is in effect a plate detector with the output load in the cathode circuit, which being of a very high order makes it impossible for grid current to flow and also introduces audio frequency negative feedback, that is to say, the audio frequency in the output circuit is fed back into the grid circuit in opposition to the audio-frequency voltage already existing. This obviously causes a corresponding reduction in gain but at the same time effects an increase in linearity and when negative feedback is sufficient to reduce the gain to the neighbourhood of unity, linearity is so improved that it is actually better than that of a diode, and has the advantage

of zero or even negative damping. Reference to Fig. 43 will show that the cathode resistor R1 is shunted by a capacitor C1 the capacity of which should be small as, with R1, it forms the time constant and must not be large enough to appreciably respond to the audio frequency. Assuming a valve with an amplification factor of 20–25 and an anode voltage of 200–250, typical values are R1 0·2 megohm, R2 0·5 megohm (volume control), C1 250 p.f., and C2 0·1 mfd. In the interests of clarity the anode of the infinite impedance detector is shown connected direct to H.T. +, in practice, however, it is usual to de-couple the anode using a bypass capacitor that offers low reactance to both radio and audio frequencies, typical values would be 10.000–20.000 ohms for the de-coupling resistor and 10 mfd. or more for the de-coupling capacitor. It is emphasized that this form of detector has no load in the anode circuit, a fact that is not upset by the de-coupling arrangements since the reactance of the de-coupling capacitor will be very small at the lowest audio-frequency. The reactance of a 10 mfd. capacitor at 50 cycles is just over 300 ohms, which is negligible when compared with the cathode load and the impedance of the valve.

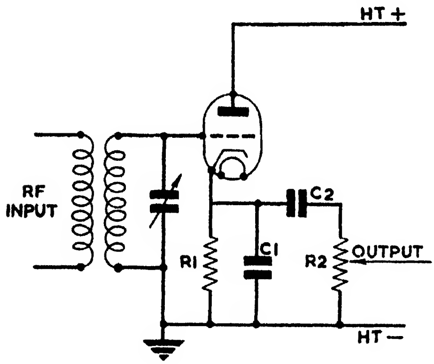


FIG. 43.
THE INFINITE IMPEDANCE DETECTOR.

The infinite impedance detector as a detector approaches the ideal, its lack of popularity being probably due almost entirely to the fact that it cannot conveniently provide a source of automatic volume control, a function that is so essential to any worth-while receiver. The addition of a diode valve would enable this function to be performed but the main advantage, namely absence of damping, would be lost.

Before leaving the subject of the use of the valve as a detector, it will be useful to summarize the advantages and disadvantages of the several basic arrangements since these tend to be somewhat conflicting.

THE ANODE BEND DETECTOR

Advantages

(*a*) A useful amplification factor is obtained for the stage as a whole.
(*b*) No grid current flows, consequently the preceding tuned circuit is not damped from this cause.
(*c*) Damping due to capacitance between anode and grid is low.

Disadvantages

(*a*) Lack of sensitivity for small inputs.
(*b*) Amplification progressively variable with input at small input.
(*c*) Distortion is high except for low modulated high amplitude input.
(*d*) Although capable of handling an input of useful amplitude the danger of running into grid current constitutes a limitation.

THE INFINITE IMPEDANCE DETECTOR

Advantages

(*a*) The maximum permissible input is virtually unlimited.
(*b*) It imposes no damping on the preceding tuned circuit due to either grid current or grid anode capacitance. In certain circumstances the input impedance is negative and therefore improves the selectivity and gain of the preceding tuned circuit.
(*c*) Distortion is very low and decreases as input increases and distortion is low at high percentage carrier modulation.

Disadvantages

(*a*) The overall amplification of the stage is less than unity if the above advantages are realized.
(*b*) A.V.C. cannot be *conveniently* incorporated without sacrificing advantage (*b*) above.

THE DIODE DETECTOR

Advantages

(*a*) The maximum permissible input is virtually unlimited.

(*b*) Distortion decreases as input increases and distortion is low at high percentage carrier modulation providing that suitable coupling arrangements are employed.

Disadvantages

(*a*) The overall amplification of the stage is less than unity.
(*b*) Considerable damping is imposed on the preceding tuned circuit.

THE LEAKY GRID DETECTOR

Advantages

(*a*) A relatively high amplification factor is obtained for the stage as a whole, and as the arrangement lends itself to transformer coupling the overall gain can be further increased.
(*b*) Distortion is not high and is acceptable up to an input of the order of 1 volt.
(*c*) Performance is high at quite small input.

Disadvantages

(*a*) Maximum permissible input is severely limited (see advantage (*b*) above).
(*b*) Damping of the preceding tuned circuit is considerable and is due to both grid current and anode grid capacity; this disadvantage can be offset by the use of reaction subject to the limitations of this principle, which is described below.

REACTION

Sufficient has been said about detector damping to make it apparent that the removal of such damping would bring about a marked increase in both sensitivity and selectivity. It is also equally apparent that the removal of other sources of damping such as that caused by the radio-frequency resistance of the tuned circuit would bring about an increase of these two qualities. A comparatively simple means of reducing grid circuit damping caused by a leaky grid detector, is by feeding back energy from the anode circuit into the preceding grid circuit in such a manner that the fed back energy is in phase with the energy already existing; the deliberate feeding back of energy for the purpose

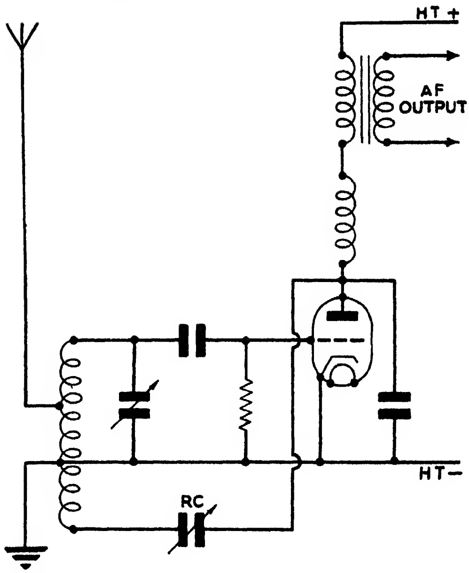


Fig. 44.—One of several methods of applying Reaction.

of reducing the effect of detector damping is known as reaction, or in America, as regeneration. Reaction appears to be a very simple way of increasing selectivity and sensitivity but must normally be provided with means of control since the amount of energy fed back will vary with frequency and must be varied with reference to the amplitude of the applied signal. When reaction is adjusted to the limit where any increase would bring about sustained oscillation the resulting increase in sensitivity is very great for very weak signals and less, although very considerable for strong signals. Such excessive use of reaction, however, brings about a grossly excessive increase in selectivity which brings about corresponding attenuation of the outer sidebands of the modulated signal thereby impairing the quality of reproduction. Reaction adjusted to this limit is called critical reaction; when reaction is adjusted to the point where it exactly offsets the damping caused by the detector valve it is occasionally referred to as "permissible reaction" a term which although beautifully expressive, has never been actually accepted into radio technology.

Various methods of applying the principle of reaction can be devised, the most popular arrangement being that shown at Fig. 44, where the actual feedback is achieved by inductive coupling, but the amount of feedback is controlled by the variation of capacity of RC. Adjustment of reaction tends to detune the tuned circuit to which it is applied, but by careful design this effect can be reduced to a minimum. Nevertheless this effect is inconvenient and constitutes a limitation on its usefulness.

An extension of the principle of reaction exists, known as super-regeneration, in which reaction is applied well beyond the point where sustained oscillation would occur, but which is prevented by momentarily stopping oscillation at a rapid rate, a process known as quenching; providing that the quenching frequency is well above audible frequency, a reasonable quality of reproduction can be obtained combined with enormous sensitivity.

AUTOMATIC VOLUME CONTROL

It has been intimated earlier in this chapter that means exist whereby the sensitivity of a receiver can be automatically con-

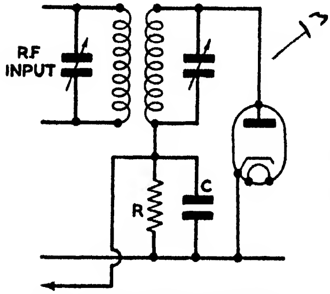


FIG. 45 (*above*).—DIODE ARRANGED FOR A.V.C.

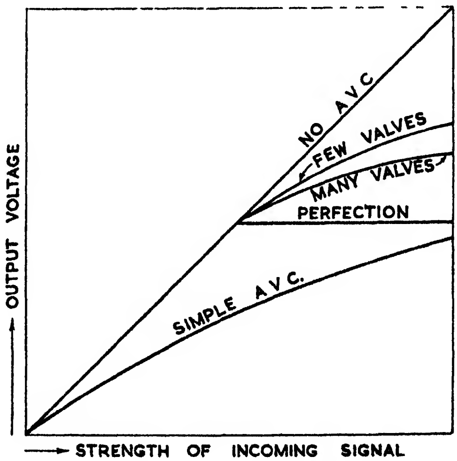


FIG. 46 (*right*).—DIAGRAM ILLUSTRATING THE EFFECT OF A.V.C.

trolled by the amplitude of the incoming signal so that within limits all stations that are received above a certain strength are reproduced at more or less equal volume. This is achieved by utilizing a D.C. potential obtained by rectifying the incoming signal to increase the negative grid potential of the pre-detector valves and thereby controlling their gain. Automatic volume control or automatic gain control as it is sometimes called, can be arranged in a variety of ways, but one example will suffice to explain the basic system in so far as it concerns the thermionic valve. Fig. 45 shows a diode arranged for automatic volume control from which it will be observed that the circuit is that of a diode detector, but it differs in the choice of value for C. The value of R must be kept reasonably high in order to develop the maximum possible voltage and may generally speaking be of the

same order of resistance as that employed for the load of a diode detector. The value of C, however, must be somewhat higher in order to produce a longer time constant which is usually of the order of $\frac{1}{5}$ to $\frac{1}{10}$ of a second and is in fact a compromise between a time constant long enough to entirely ignore modulation and short enough to follow changes of signal input due to fading.

It is clearly desirable that automatic volume control should reduce all signal inputs to a common level that are initially strong enough to overload whichever stage in the receiver is most easily overloaded, but should be inoperative on inputs of lesser amplitude in order that they are not further reduced. Automatic volume control arranged in this way is referred to as delayed A.V.C. and in practice the diode is biased so that it is inoperative until a certain amplitude level of signal is reached when it commences to function in the normal manner. The diagram, Fig. 46, expresses several conditions of A.V.C. compared with perfection and the characteristic of a receiver not fitted with this refinement. In the interests of completeness a circuit diagram is included at Fig. 47, which shows the conventional arrangement of a double diode triode whereby one diode is used for detection and the other for automatic volume control. In the variation shown, the A.V.C. diode is operated from the intermediate frequency transformer primary which tends to produce quieter tuning as the A.V.C. diode commences to work (as the tuning capacitors are turned) before the detector diode providing that the band-width of the primary is wider than that of the secondary which is almost always the case.

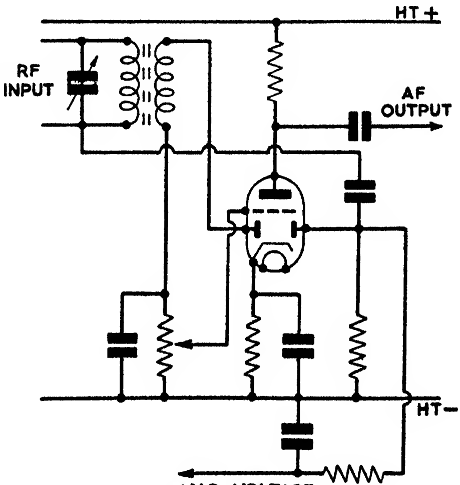


FIG. 47.—A POPULAR ARRANGEMENT OF THE DOUBLE DIODE TRIODE FOR DETECTION, A.F. AMPLIFICATION AND A.V.C.

Further information on automatic volume control will be found in Chapter XV.

THE VALVE AS AUDIO-FREQUENCY AMPLIFIER

Audio-frequency amplification is dealt with elsewhere and since, in this rôle the valve acts as a straight amplifier, little comment is called for in this chapter, except to remark on the peculiar tendency in this country to associate the triode with this particular function automatically. The pentode can be employed as a perfectly good audio-frequency amplifier and has largely superceded the triode for this purpose in America ; it is true that before the introduction of 6·3 volt valves in this country the choice of pentodes available was not ideal, but nevertheless some of the lower impedance radio-frequency pentodes could be used satisfactorily under suitable operating conditions. As an audio-frequency amplifier the pentode has the advantage of high gain, and extremely low harmonic distortion can be achieved by employing negative feedback, a principle that is discussed later on in this chapter.

The relationship between anode load and the performance of an amplifier has already been discussed, but considerable scope still remains for consideration of the effect of anode load on the output stage. Perhaps the best way of illustrating the influence of the output load is by taking a typical output valve and analysing the performance with the correct or optimum load and some other value of load. Reference to Fig. 48 will show a typical family of anode-volt/anode-current curves of a medium sized, directly heated, output triode. The correct load line,

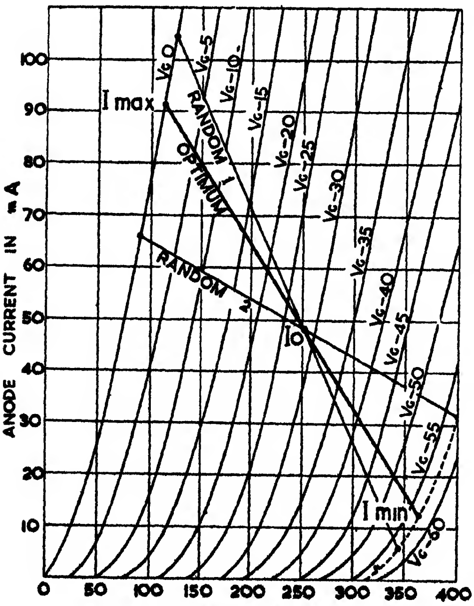


FIG. 48.—ANODE-VOLTS/ANODE-CURRENT CURVE OF A 25 WATT TRIODE.
With various load lines to illustrate the text.

3,000 ohms, shown by heavy line, swings from zero grid volts to -57 grid volts, the latter being double the grid bias voltage. The load line is most conveniently determined by marking the operating point which is the coincidence of the operating anode voltage and grid voltage, and in the example under discussion, is 250 volts and $-28{\cdot}5$ volts respectively, designated I_0. The next step requires a special transparent ruler which is engraved so that the divisions on one side bear a ratio of 11:9 to the divisions on the other side. The centre zero is placed on the operating point I_0, and the scale revolved until the division nearest to V_g0 bears the same number as the division nearest to $V_g\ -57$. A line is then drawn from V_g0 to $V_g\ -57$, which is double the grid bias. It is now possible to determine the power in the load resistance which is the useable output of the valve and is calculated by the following simple formula :—

$$\frac{\frac{1}{8}\,(\text{I max.} - \text{I min.}) \times (\text{V max.} - \text{V min.})}{1000}$$

When I max. = maximum anode current in milliamps, I min. = minimum anode current in milliamps, V max. = maximum anode voltage in volts and V min. = minimum anode voltage in volts.

In other words, the output is calculated by multiplying the difference between the maximum and minimum anode current by the difference between the maximum and minimum anode voltage, and dividing the result by 8,000. With the aid of Fig. 48, the above formula can be employed and the output ascertained. Maximum anode current is 92 milliamps. and the minimum anode current is 12 milliamps. ; the maximum anode voltage of the swing along the load line is 363 and the minimum is 113 volts. Thus—

$$\frac{\frac{1}{8}\,(92 - 12) \times (363 - 113)}{1000} = 2{\cdot}5 \text{ watts.}$$

It will now be interesting to ascertain the value in ohms necessary to reproduce the condition of this load line. This is a simple application of Ohm's Law. The change in current was 80 milliamps. for a change of voltage of 250 volts, since, for the application of Ohm's Law, the current must be in amps. if the voltage is in volts, the load is determined by—

$$R = \frac{V}{I} \qquad\qquad R = \frac{250}{0{\cdot}08} = 3{,}125 \text{ ohms.}$$

The next step is to investigate the performance of the valve using the random optimum load represented by the line marked "random 1." Inspection will show that the maximum anode current is 105 milliamps. and the minimum 6 milliamps., and that the maximum anode voltage is 340 and the minimum 125. Applying the formula—

$$\frac{\frac{1}{8}\,(105 - 6) \times (340 - 125)}{1000} = 2 \cdot 7 \text{ watts.}$$

By applying Ohm's Law to determine the value of the load represented by the line marked "random 1" as already explained—

$$R = \frac{V}{I} \qquad\qquad R = \frac{340}{0\ 099} = 2{,}170 \text{ ohms approx.}$$

Attention can now be turned to the question of distortion. In the case of the 3,000 ohm load, second harmonic distortion is just over 5 per cent., but in the case of the 2,100 ohm load it is just over 8 per cent. Investigation of the load line "random 2" will show that the output falls off to 1·3 watts with a second harmonic distortion of 2·9 per cent., the load line representing a load of 9,000 ohms. From this it may be deduced that when the optimum load is too high, harmonic distortion tends to decrease, but power output is seriously reduced and when the load is reduced harmonic distortion increases rapidly.

Comparison of the above quoted examples with the curve in Fig. 49 will show a few very small discrepancies. This is because great accuracy, when using a curve such as that shown at Fig. 48, is not possible, unless it is of very large dimensions; when quoting examples it is preferable to present figures as readable from a graph as printed, and not to indulge in the habit of modifying such figures to obtain absolute consistency. The formula for determining second harmonic distortion from a triode valve is given below:—

$$\frac{\dfrac{\text{Imax} + \text{Imin} - \text{Io}}{2}}{\text{Imax} - \text{Imin}} \times 100 \text{ per cent.}$$

When Imax = maximum anode current, Imin = minimum anode current, and Io = anode current with no signal.

While the examples given above of correct and incorrect loading illustrate a number of points, they only show isolated instances and give no continuous picture; reference is therefore

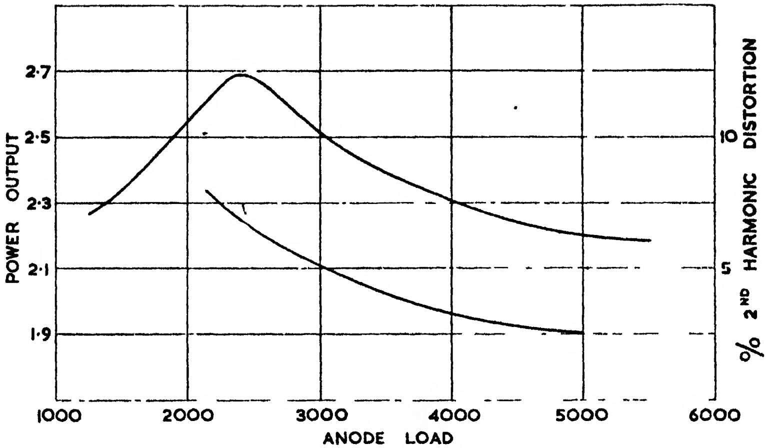


FIG. 49.—THE RELATIONSHIP OF ANODE LOAD TO POWER OUTPUT (UPPER CURVE) AND SECOND HARMONIC DISTORTION OF A TRIODE VALVE.

made to Fig. 49, which shows the relationship between available power output and anode load, and between harmonic distortion and anode load plotted together, the valve used in the preparation of this graph was a triode of medium power. A study of this illustration reveals the fact that the desirable value of load is clearly not that which gives maximum output since such a value gives an unreasonably high percentage of harmonic distortion. It is apparent that in the case of a single output valve, maximum power output and maximum undistorted power output each have a separate meaning; when two triode valves are used in push-pull, however, these two terms become more nearly identical since the load value may be chosen with more regard for maximum power output, and less regard for the question of distortion since the even harmonics tend to be cancelled out by push-pull working, and odd harmonics are most unlikely to be generated by a triode valve at significant percentage.

THE POWER OUTPUT TETRODE AND PENTODE

Attention can now be directed to the pentode output valve and, in general, considerations governing the selection of operating conditions for the output pentode apply equally to both. This is a radical departure from the high impedance screened pentode

and tetrode and some comment is obviously called for. It will be recalled that the usefulness of the high-frequency tetrode was reduced by the secondary emission kink, due to the screening grid acting as a collector for electrons. In the output tetrode it is possible to almost entirely eliminate this kink by valve geometry, advantage being taken of the fact that the high voltage grid is not required to act as a capacity screen between control grid and anode, and may, therefore, be shaped to conform with certain requirements. As already explained, the tetrode kink is caused by electrons reaching the high voltage grid, which is prevented in the output tetrode by persuading the electrons to travel along carefully chosen paths, and preventing possible secondary emission from the anode from bouncing back to the high voltage grid by what is in effect a space charge " grid " formed by the electron stream itself. In other words, electrons in the vicinity of the anode form, in effect, a suppressor grid.

The special control of the electron stream is brought about in two ways. Obviously two dangers exist, electrons proceeding

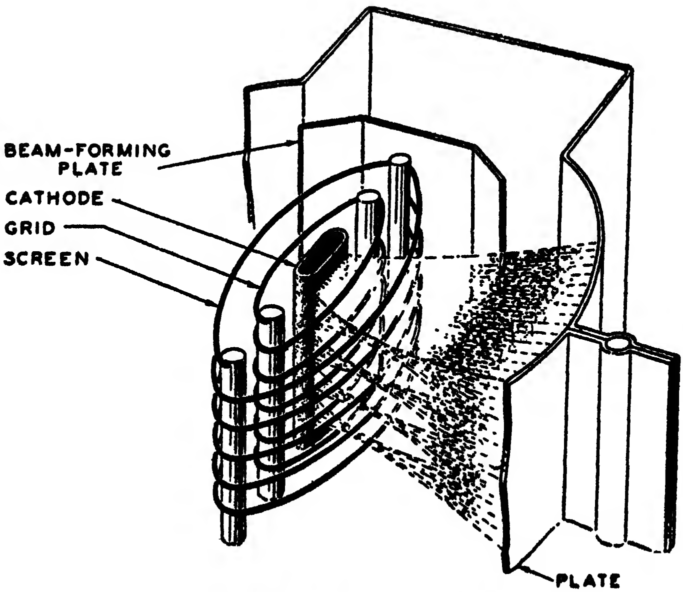


FIG. 50.—BEAM TETRODE VALVE.
The beam forming plates of this valve marshal the electron stream in the manner illustrated. (R.C.A.)

direct from cathode to the screen grid, and electrons bouncing off the anode and flowing to the screen grid. The first named danger is overcome to an adequate extent by making the spacing of the control and screening grids so related that the control grid throws what may be termed an electron shadow on the screening grid. The streams of electrons, having passed through both grids, join up and impinge on the anode in a solid pattern, but clearly some of these would bounce back were it not for the barrier formed by the space charge already referred to; for the purpose of the present discussion, the space charge may be regarded as a thickening in the electron stream which must take place in the area between screening grid and anode in the manner which it has been attempted to illustrate in Fig. 50. It remains to explain how this increased density in the electron stream is formed; consider for a moment how a bottleneck forms in a stream of traffic, cars may proceed along a road at, say, 50 miles an hour at intervals of 100 yards, but when some point is reached where a lesser speed has to be employed the spacing between the cars becomes correspondingly less. In the same way, the electrons proceeding from cathode to anode in their well-ordered streams will increase in density in the required area if they can be slowed up, which is exactly the phenomenon that occurs; the slowing up being achieved by producing a low velocity region, the position and de-acceleration of which is controlled by the distance of the anode from the other electrodes. This remarkable procedure is assisted, in certain tetrodes, by a pair of plates held at cathode potential, to assist in forming the electron layers; the edges of the plates are arranged to coincide with the space charge area and extend the space charge beyond the electron stream, thus preventing stray secondary electrons from reaching the screen around the edge of what would otherwise be the limitation of the space charge area. Such a tetrode is known as a beam tetrode, the general construction of which may also be seen at Fig. 50.

The power output pentode or tetrode has many advantages over the output triode and is capable of delivering a larger output for a given power input and input signal voltage than is the case with the triode. The pentode, however, is less tolerant than the triode regarding operating conditions, which must be carefully selected if distortion is to be kept within reasonable bounds. The pentode or tetrode generates both

second and third harmonic distortion at significant amplitude, but, generally speaking, third harmonic distortion tends to reach undesirable proportions, while second harmonic distortion can be made insignificant by the correct choice of anode load. There are, however, exceptions to this rule, the Cossor PT41B being a notable example; the relationship between anode load, power output and second and third harmonic distortion of a typical output pentode is shown in Fig. 51. It will be observed that anode load has a marked influence over both power output and harmonic distortion; at no point is the

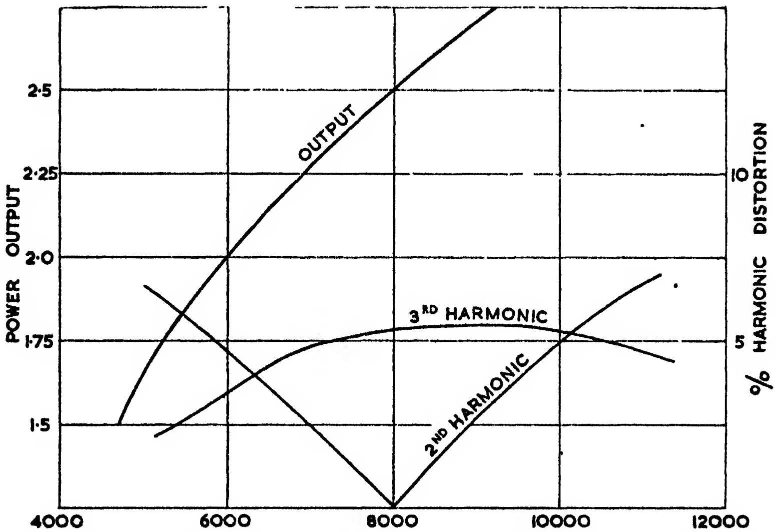


FIG. 51.—THE RELATIONSHIP OF ANODE LOAD TO POWER OUTPUT AND SECOND AND THIRD HARMONIC DISTORTION OF A PENTODE VALVE.

total harmonic distortion below 5 per cent., while third harmonic distortion can only be reduced below 5 per cent. at a serious loss of output power or intolerable total harmonic distortion. The makers of the valve in question recommend 8,000 ohms, which gives low or negligible second harmonic distortion with about 6 per cent. third harmonic distortion and an output of 2·5 watts. As 6 per cent. third harmonic distortion is displeasing to even an untrained ear, it is desirable that these figures be reduced by the application of negative feedback, a principle which is discussed later.

All discussions on the subject of the anode load of the output valve have assumed the load to be pure resistance whereas in practice it will be an impedance, the value of which will unfortunately vary with frequency and will result in the effective load being different at various frequencies. Unless some limiting factor is introduced, the rise in impedance at the higher musical frequencies will produce extremely unpleasant distortion in the case of the output tetrode or pentode, a glance at Fig. 51 will show the results to be expected for only a 50 per cent. increase in impedance. It is therefore common practice to shunt an inductive load with a resistor and capacitor in series, values being so chosen that the capacitor has a reactance many times that of the anode load at the very low audio frequencies, but comparable to it at the higher audio frequencies, common values are 0·01 mfd. in series with 10,000 ohms. Clearly, however, this simple palliative is a long way from perfection unless aided by other means, one of which is undoubtedly the application of negative feedback.

Negative Feedback

Reference has been made in an earlier paragraph to the principle of reaction, which is the feeding of energy from the anode circuit of the detector back into the grid circuit, so phased that the fed-back energy adds to the existing energy and among other things increases sensitivity. This is called positive feedback. Attention is now directed to negative feedback which is energy fed back in such phase relationship that it is in opposition to the existing energy in the grid circuit whereby it reduces the effective gain of the stage but introduces a number of important advantages, including a reduction of harmonic distortion.

Negative feedback may encompass a single stage or several stages, but can only correct distortion in the stage or stages to which it is applied, and it is emphasized that it will not correct distortion which occurs before or after the stage or stages to which negative feedback is applied. The improvement in harmonic distortion is approximately equal to the reduction of stage gain and if optimum feedback is employed the reduction in gain will often render it necessary to introduce an additional stage of amplification. In addition to reducing harmonic distortion, audio frequency negative feedback increases stability, reduces noise and hum, improves the linearity of frequency

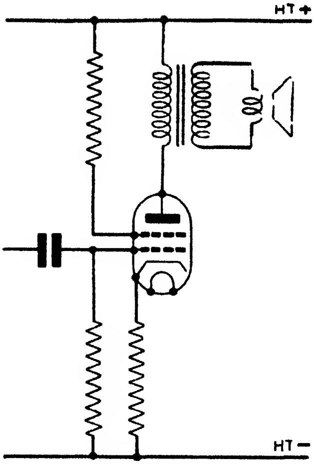


FIG. 52.—THE SIMPLEST FORM OF NEGATIVE FEEDBACK BY OMISSION OF THE CATHODE BY-PASS CAPACITOR.

response and reduces the effective impedance of the valve which straightens out the valve's characteristics and if the load is inductive, as it is in the output stage, variation of impedance with frequency will produce less distortion.

Negative feedback can be readily classed under two headings, current feedback and voltage feedback. Negative voltage feedback may be defined as the condition existing when the voltage fed back is proportional to the voltage across the output load which provides a reduction in the effective internal resistance of the amplifier. Negative current feedback is the condition when the fed-back voltage is proportional to the current flowing through the output load, this condition unfortunately increases the effective internal resistance of the amplifier.

The simplest form of negative current feedback is the omission of the cathode resistor by-pass capacitor. A glance at Fig. 52 will show that the bias resistor is common to both anode and grid circuit, and as it is in series with the anode circuit, a potential difference will be developed across it proportional to the anode current. The potential difference thus developed across the bias resistor will appear between grid and cathode in opposition to the existing signal voltage. Negative current feedback has the advantage of great simplicity

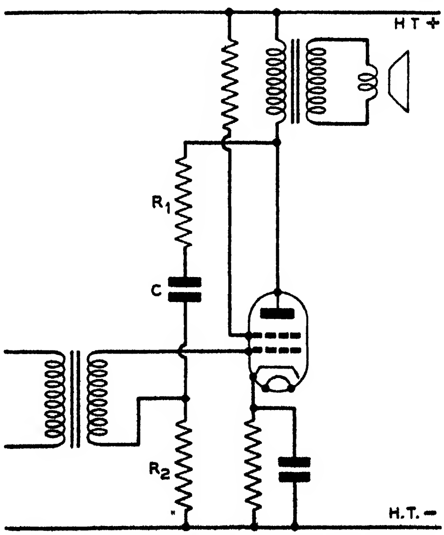


FIG. 53.—A SATISFACTORY ARRANGEMENT FOR NEGATIVE FEEDBACK.

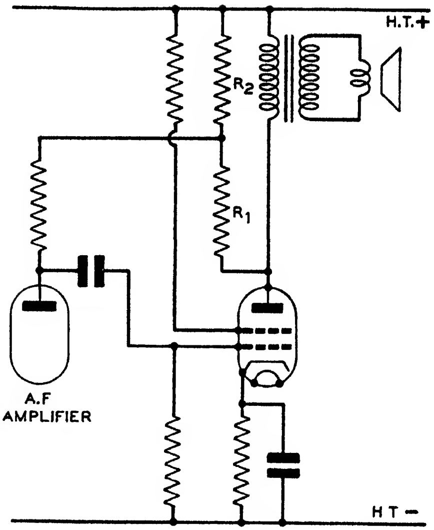


FIG. 54 —A PARTICULARLY SATISFACTORY ARRANGEMENT FOR NEGATIVE FEEDBACK WHEN THE OUTPUT IS PRECEDED BY R.C. COUPLING.

and provides the same decrease in harmonic distortion for a given gain reduction, as does negative voltage feedback, but, as already stated, it increases the effective internal resistance of the amplifier. When less negative current feedback is desired than that developed by omititng the cathode bias capacitor, the resistor is tapped as desired and the capacitor connected across that portion of the resistor which is not intended to provide feedback.

A typical circuit of negative voltage series feedback is given in Fig. 55, the degree of feedback being controlled by the relationship of R1 to R2, the value of C should be so large that its reactance is negligible. With resistance coupling, negative feedback is not quite so easy to arrange, but the circuit shown at Fig. 54 is very satisfactory. In conclusion, a form of parallel feedback is shown in Fig. 55 and is intended to illustrate the type of arrangement to be avoided, as it makes the input impedance of the output valve very low, but if it is employed as a matter of convenience the value of the coupling capacitor must be increased to offset the bass attenuation which would otherwise result.

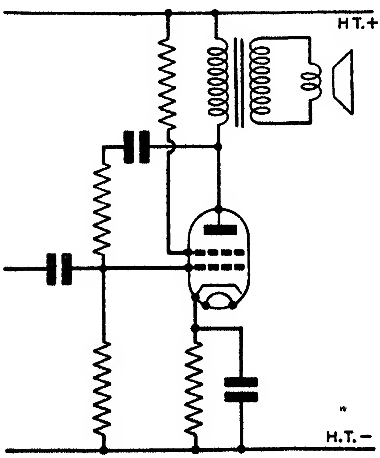


FIG. 55.—A FORM OF NEGATIVE FEEDBACK THAT IS NOT RECOMMENDED.

MULTI-ASSEMBLY OUTPUT VALVES

Output valves are sometimes combined with other electrode assemblies in the same bulb, a common example being the Cossor 42 O.T.D.D., a double diode output tetrode intended to perform the dual purposes of detector, automatic volume control and output. Other examples include the combination of output valve and mains rectifier, such as the 70L7–GT, an arrangement common in midget receivers, twin triodes and pentodes intended for Class B and quiescent push-pull output respectively, and such valves as the 6F7, a triode and radio frequency pentode which, having independent grids, can be used for a variety of purposes where space economy is desirable. Perhaps reference to multi-assembly output valves would be incomplete without historical reference to the Lowe valve which comprised three separate electrode assemblies, complete with resistance capacitive coupling, all incorporated within a single valve bulb and comprising two stages of R.C. coupling and output valve as one single entity.

THE VALVE AS A RECTIFIER

The action of a mains rectifier valve is similar to that of the detector since detection and mains rectification is fundamentally the conversion of alternating current to direct current, but whereas it is desired to preserve the changes in amplitude due to modulation in the case of the detector, it is desired to reduce any amplitude variation to a minimum in the case of the mains rectifier. These two distinct requirements are brought about by the associated components, the action of the valve being the same in each case ;. furthermore, the detector valve is called upon to rectify a very small current at a moderate voltage, whereas the mains rectifier is normally required to deliver a relatively large current at considerable or high voltage. As a matter of convenience it is preferable to reserve the term " detection " where it is desired to retain an audio frequency component and " rectification " where it is intended to convert A.C. power into D.C. power. A mains rectifier is essentially a diode, the action of which has already been described. Attention can therefore be straightway directed to practical aspects

of mains rectification, a subject that is sometimes treated more lightly than it deserves to be.

Fig. 56 shows a typical rectifier circuit employing single wave rectification, the arrangement shown being known as the capacity filter input which is commonly used in broadcast receivers. The capacitor C1 should preferably be of the non-electrolytic type and of moderate capacity to prevent the surge current passing through the rectifier from reaching excessive proportions. The capacitor C2 should be as large as necessary to give the requisite smoothing in conjunction with the associated inductance. When selecting capacitors for this purpose it should, of course, be borne in mind that A.C. peak voltage is 1·4 times

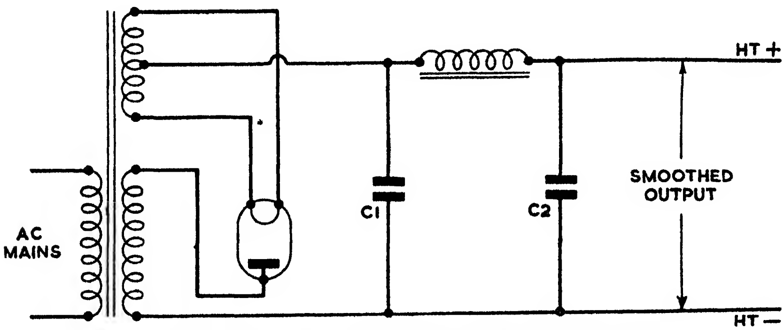


Fig. 56.—A Typical Single Wave Mains Rectifier.

the R.M.S. voltage and capacitors should therefore be selected with an adequate voltage rating.

In certain circumstances the capacitor C1 (Fig. 56) is sometimes omitted, the arrangement then being known as choke filter input and while it has the disadvantage of giving a lower D.C. output voltage, it has the advantage of improved voltage regulation and a lower peak rectified current.

Rectifier valves are available as single assemblies or twin assemblies intended for full wave rectification and may have directly or indirectly heated cathodes, the latter having the advantage of allowing the valves which form the load, to warm up and be ready to take current before appreciable high tension voltage is developed, thus preventing the latter from reaching an abnormally high value on first switching on. Usually the

cathode is internally connected to the heater, but in certain specialized types separate connection is made, the insulation between cathode and heater being capable of withstanding high voltage so that the valve may be used as a voltage doubler, a system so called because the D.C. output can approach twice the peak value of the A.C. input. This arrangement is illustrated by the circuit diagram at Fig. 57, which, although it has no mains transformer to step up the voltage, can easily give a smoothed output of over 600 volts from an input voltage of 230 volts R.M.S. As a matter of interest rather than practical value, the circuit of a voltage quadrupler arrangement is shown in Fig. 58 which would deliver a D.C. smoothed output of some 1,200 volts from an input of 230 volts R.M.S.; the arrangement is, however, somewhat impractical since, so far as the writer is aware, there is no rectifier valve commercially available which would stand such a voltage between heater and cathode.

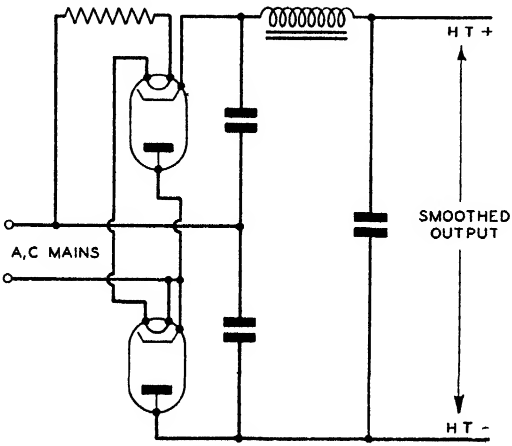


FIG 57.—A RECTIFIER VALVE ARRANGED FOR VOLTAGE DOUBLING.

The Mercury Vapour Rectifier

Mention may now be made of the mercury vapour rectifier, which, unlike most valves, is not pumped to high vacuum but contains mercury vapour at low pressure; it is otherwise similar to a normal high vacuum rectifier, but has the advantage that the voltage drop between cathode and anode is independent of the current drawn, although it is slightly dependent on bulb temperature. Such rectifier valves are particularly advantageous when very large currents are required, or when voltage regulation is of paramount importance.

The action of the mercury vapour rectifier is comparatively straightforward, the atoms of the mercury vapour come into violent collision with the electrons passing from cathode to anode, causing additional electrons to be knocked out of the mercury atom, which is then said to be ionized since it is deficient of one or more electrons, and therefore has a positive charge. Ionization neutralizes the space charge within the valve and an increased number of electrons is available.

The mercury vapour rectifier is very susceptible to damage since it has no limiting properties in the event of overload and can arc back, i.e. pass current in the wrong direction at high

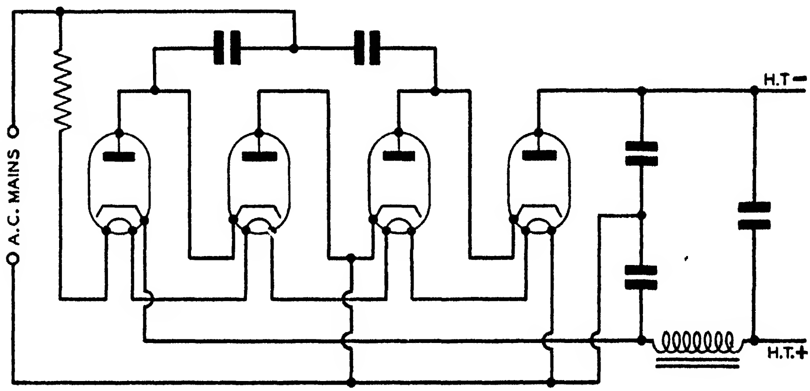


FIG. 58.—CIRCUIT OF A VOLTAGE QUADRUPLER SHOWN PURELY AS A MATTER OF INTEREST.

inverse peak voltages ; arc back sometimes occurs if the cathode is operated below normal temperature. It is essential with this type of rectifier that the cathode be allowed to reach its correct working temperature before the anode voltage is applied ; a time delay of 20 to 30 seconds is therefore required. To prevent the possibility of error, a time delay switch is usually employed. As a further safeguard, some means should be employed to limit the current, or fuses inserted in the anode leads for protective purposes. The flow of current at the commencement of each half cycle starts abruptly, often causing objectionable interference, similar to mechanically making and breaking a circuit, and it is customary therefore to screen the entire valve, with due regard to the need for proper ventilation, or alternatively, to insert a radio-frequency choke in each anode lead

and to connect a capacitor of adequate voltage rating between each side of the transformer secondary and earth. Typical values are 1 millihenry and 0·1 mfd.

The Ionic-heated Cathode Rectifier Valve

This valve, of which the American OZ4 is typical, is a gas filled cold-cathode rectifier introduced primarily to replace vibrator type H.T. supply units and is included rather more from the point of interest than wide usefulness. The valve comprises two anodes and a cathode coated with electron-emitting material, the bulb being filled with an inert gas at very low pressure. The expression, cold-cathode, is to some extent a misnomer, as the cathode becomes heated not by a heater wire but by ionic bombardment. Ionization of the gas occurs between the cathode and the anode which is positive (at any particular instant); since ionization does not occur between the cathode and the anode which is negative at the same instant, the necessary condition for rectification is satisfied.

The voltage drop between anode and cathode is somewhat higher than that obtaining in the mercury vapour rectifier due to the loss of energy employed to heat the cathode. Should a rectifier of this type be employed for any purpose where the current drawn falls on occasion to zero, a bleeder resistor must be employed so that sufficient current is drawn at all times to maintain the cathode at working temperature.

THE GAS-DISCHARGE TRIODE

The gas discharge triode, sometimes called the thyratron, is introduced at this point as a matter of convenience, as it is fundamentally different in theory and application from any other form of triode. The fact that it has followed two gas filled rectifiers should not necessarily cause it to be classed with them, admittedly it can be used as a rectifier, but so can any other form of valve; actually the most common use of the gas discharge triode is in the time base of the television receiver and cathode ray oscillograph.

The gas discharge triode usually has an anode made somewhat on the pattern of a Venetian blind, the anode being brought to a top terminal which gives the assembly something of the appearance of a screen grid valve; it is, however, a triode and

the bulb is gas filled at very low pressure. The behaviour of the valve is somewhat unusual, since it either passes unlimited anode current or no current at all. There are no graduations between these extremes. According to the structure of the particular valve there is a value of grid voltage that will entirely prevent the flow of anode current, but when this value of negative grid voltage is reduced below the critical value all out anode current flows, the value of which is only limited by the external circuit. If no such limitation exists the valve will destroy itself. It is particularly important to note that when once anode current has commenced to flow, the grid loses control and will not affect the flow of anode current, however negative it may be made; anode current can only be stopped by breaking the anode circuit or in some other way causing the anode to cease being positive in respect to the cathode. The gas discharge triode can also be used as a rectifier, alternating voltage being supplied to both anode and grid and any desired average current may be taken from the valve, control being exercised by adjusting the phase between grid and anode.

Gas discharge triodes intended for use as rectifiers or relays sometimes have a mercury vapour gas and require an appreciable de-ionization time of the order of 100 microseconds or more to permit the grid to regain control after the anode current has been stopped. Similar valves, intended for use in time bases, usually have an argon gas filling and have a de-ionization time of 10 microseconds or less, but even this can be considerably shortened by limiting both the peak and mean anode current.

The gas discharge triode is symbolized like a high vacuum triode, but the area contained within the outer rim is usually shaded, although American publications normally indicate the presence of gas by a single black spot.

TRANSMITTING VALVES

Speaking very broadly, transmitting valves differ from receiving valves only in their ability to handle larger power, but to meet this requirement very specialized construction has been evolved particularly for transmitting valves intended for very high frequency working. A valve that will oscillate for thousands of hours at medium frequency will completely collapse at very high frequency, even under greatly reduced operating

conditions. When a really large power has to be handled, the problem of cooling becomes paramount and water-cooled valves are in common use. High temperature produces another problem, namely, that of retaining a sufficiently high vacuum and some of the largest transmitting valves are continuously evacuated.

The need for generating high, instantaneous power at centimetric frequencies brought about by the advent of radar has introduced some truly remarkable devices; the word "device" is deliberately used in preference to the word "valve," amongst which the magnetron must take pride of place. Specialized radar valves are dealt with separately in the chapter devoted to radar, since they are so intimately linked with their associated apparatus that they are difficult to discuss as independent units.

A GENERAL SURVEY

A leading valve manufacturer would probably not object to the use of the word "fantastic" to describe the present lack of standardization and type duplication of domestic receiving valves. Ranges of valves exist which are electrically interchangeable but which have different bases, and *vice versa*; valves appear as separate types in the same range, but differing so little that one is at a loss to see why a single type midway between them could not easily cover the potentialities of both.

There are big valves, small valves, miniature valves, acorn valves, even smaller valves recently removed from the secret list, there are valves intended for A.C. operation, neatly duplicated, except in respect of their heater voltage, by corresponding ranges that are not only suitable for A.C. working but D.C. working as well: this latter class is sometimes blushingly referred to as the Universal range, and while it was launched with good intentions when originally introduced, it is doubtful if anything less universal in character could be conceived than the range as it now exists.

Perhaps the strongest argument against valve type specialization was the existence of a multi-valve superheterodyne marketed by a well-known manufacturer a few years before the late war, which used a single type of valve as radio-frequency pentode amplifier, pentode mixer, triode oscillator, intermediate frequency amplifier, second detector and A.V.C., audio-frequency

amplifier and push-pull triode output. The valve used to perform these numerous functions was a radio-frequency screened pentode, the anode suppressor grid and screening grid being strapped together to form a triode valve where required; it is not suggested that such an arrangement is necessarily the most efficient, but the convenience to the user who need only keep a single valve to act as replacement for any valve holder does not need emphasis.

It is understood that the valve industry appreciates the need for standardization and it may be hoped that such a state may soon exist in this country, although not necessarily to the same extent as that obtaining in America, where some authorities consider standardization to have reached a point detrimental to progress.

The remarks made above in this survey, while giving a general picture, do little to guide the reader through the labyrinth of upwards of a thousand types of receiving valves listed in contemporary catalogues. It is hoped, therefore, that the following grouping of valve types will be found helpful.

Battery valves naturally form a class by themselves and are either of the 2-volt type intended for use with an accumulator, or the 1·4 volt type intended for use with dry batteries.

The 4-volt A.C. mains group is essentially British, and up to the outbreak of war could fairly be regarded as the standard valve for A.C. mains working.

The 2·5 volt A.C. mains group is essentially American, and in that country occupied the same position as the 4-volt A.C. mains valve in Britain. This group of valves had a long run of over ten years.

The "6·3-volt" range forms the backbone of domestic receiver valves, and has naturally developed into two sub groups, one group intended for A.C. mains working is designed so that the heater voltage is constant but the heater current is increased in those types where high heater wattage is necessary, and the other group intended for A.C./D.C. working where the heater current remains constant but the heater voltage is increased in those types where high heater wattage is necessary, such valves are usually 6·3 volt or 12·6 volt at 0·3 amp., whereas the first-named sub-group usually have heater currents of 0·3 amp. or 0·6 amp. at 6·3 volts, but again there are minor exceptions.

There is another variation generally similar in conception to the group referred to above as the 6·3-volt range, but which has a heater current of 0·15 amp. and heater voltages running as high as 35 volts or more which are particularly useful in very small midgets, it being possible to arrange a combination of such valves, the heater voltages of which total, or nearly total, 110 volts. As this is the domestic voltage common to American mains supplies, the difficulties attendant on the heater dropping resistors are thus eliminated.

The last of these entirely unofficial groups must contain the acorn valves and other miniature valves especially designed for high efficiency reception on the very high frequencies, where special valve geometry is necessary to reduce the length of leads and spacing between electrodes, as at these frequencies the point is reached and passed where the time taken for electrons to travel from cathode to anode becomes a serious limiting factor.

CHAPTER XII

RADIO-FREQUENCY AMPLIFICATION

In a radio or high-frequency valve amplifier, the modulated radio frequency signals are received from the aerial circuit, increased in intensity and then passed on to the next valve. The signals are thus made more powerful without altering their character. Not all radio receivers include a high-frequency valve stage, so that it is obvious that reception of some sort can take place without it, and it is not absolutely essential in order to make a receiver work. It is natural, therefore, to inquire why high-frequency amplifier stages are used, and what are the advantages gained thereby.

Advantages

✓First of all, a high-frequency amplifier enables weaker signals to be received and so extends the range of the amplifier and makes possible the reception of more distant stations. Then there is another and possibly greater advantage, viz. that of increased selectivity. The larger the number of tuned circuits in a receiver, the higher the degree of selection which can be made between stations whose carrier waves are close together and which would otherwise spoil reception by interfering with each other. Finally, there is the advantage that a much stronger signal can be fed to the detector valve. This valve does not function satisfactorily with signals below a certain minimum strength. The distant transmitter may have a power output of kilowatts, yet the energy in the received signals is very small, possibly a fraction of a microwatt, and quite insufficient to operate the detector valve at its maximum efficiency, except in the case of a nearby station.

The Function of the Radio-Frequency Valve

For certain reasons, which have already been referred to in the chapter on Valves and will be discussed later, the high-frequency valve of a modern receiver is a screen pentode. Normally,

with the set switched on but no signals being received, the grid of the valve will be negatively biased by the voltage drop across the cathode resistor in the case of a mains valve, or by a separate grid-bias battery in a battery set, and there will be a steady anode current through the valve. The modulated radio-frequency signals received by the aerial (Fig. 1*a*) will pass through the coupling circuits to the grid of the high-frequency valve, and there they will cause variations in the negative bias voltage (Fig. 1*b*). The actual fluctuating component of these voltages are the same in character, but stronger than those in the aerial circuit.

Anode Current Variations

Ignoring for the moment the existence of any components in the valve anode circuit, at any instant when the grid is made less negative, there will be an increase in anode current. Likewise, if the grid becomes more negative, the anode current will decrease. Thus the radio-frequency voltages on the valve grid

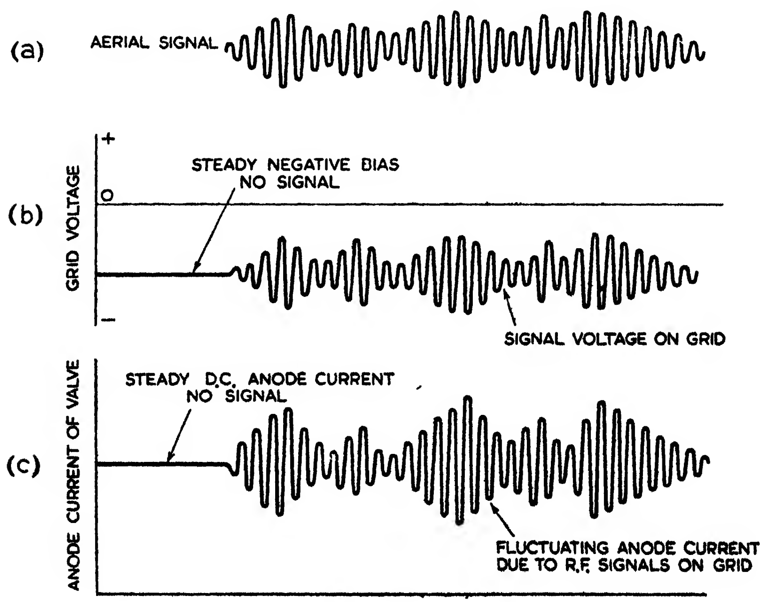


Fig. 1.—Anode Current Variations.
(*a*) Radio-frequency signals in the aerial. (*b*) Variations of grid voltage.
(*c*) Corresponding changes in anode current.

produce corresponding but much larger fluctuations in the anode current above and below the steady value which it has when no signals are being received.

Now we have to consider how these current changes can be passed on as voltage changes to the next valve, because we must remember that the valve is essentially a voltage-operated device. This is achieved by the use of a resistance, tuned circuit or choke in the anode circuit between the valve and the H.T. supply and constitutes the " load " to provide voltage changes to pass on to the next valve.

For the purpose of a simple explanation we will assume that the anode load is a pure resistance. Actually, in practice, a high-frequency choke or tuned circuit is preferred because these components function much better, but for the moment the assumption of a resistance load will serve our purpose.

Now, when the anode current increases, the voltage drop across this resistance also increases ; when the current decreases, this voltage drop falls. Since one end of the resistance is held at a constant potential, viz. that of the high-tension supply, the other end connected to the valve anode must fluctuate with the change in anode current and at radio frequency, just as the grid voltage fluctuates, but with one important difference. The anode current is a maximum when the anode potential is a minimum, and *vice versa*, so that the anode voltages are magnified copies of the grid voltage changes, but exactly opposite in phase.

Steady and Fluctuating Components

We must remember that both the anode current and the anode voltage consist of two components—a steady component which exists alone when no signals are being received and a varying component which is a magnified version of the signals coming into the aerial. Only the fluctuating component of the anode voltage is utilized, since this carries the music and speech frequencies. The steady components are necessary in order to make the valve circuit function.

In consequence, the valve anode is connected to the next valve through a condenser or transformer, so that the steady voltage component is excluded and only the variable voltages passed on. Incidentally, there is another important reason why

the coupling must be made through a component which is non-conductive to direct current. If the coupling was made conductive, the full high tension supply voltage would be applied to the grid of the next valve and a highly positive grid would rapidly result in destruction of the valve by total loss of cathode emission.

Anode Load

Although a resistance load can be used for a high-frequency amplifier, a high-frequency choke preferably tuned, or an air cored transformer functions much better. One disadvantage of a resistance load is that there is a steady voltage drop across it due to the direct current component and the voltage available at the valve anode is always less than the high tension voltage by this amount. Though this may not seem important, since the steady voltage is not involved in the signals eventually extracted, it does mean that the valve will not work so well when its anode voltage is reduced.

A high-frequency choke, it will be recalled, offers a very high obstruction or impedance to high-frequency currents, so that these produce appreciable voltage changes across the coil and these voltage changes are passed on to the next valve.

While a choke is better than a resistance as a high-frequency load, a tuned circuit is better than either because it can be adjusted to give maximum amplification at the frequency of the station it is desired to receive and to have much lower amplification at other points. Like the tuned grid circuit, it comprises a coil and condenser in parallel. Such a parallel circuit develops a high voltage across its terminals at the frequency to which it is tuned. This is a great advantage, because when the circuit is tuned to the station it is desired to receive, the sensitivity of the set is a maximum at this point, and the transmissions from other stations on nearby wavelengths are received at much lower strength. Thus a tuned circuit is much more selective than an aperiodic choke.

In practice, the condenser of the tuned anode circuit is ganged to the condenser of the aerial and/or grid circuit so that both tune together automatically when the condenser knob is rotated to that part of the scale on which it is desired to receive signals.

Types of Radio-Frequency Circuit

A high-frequency amplification stage is shown in Fig. 2 (*a*) with a tuned anode load. In Fig. 2 (*b*) the tuned circuit is replaced by an aperiodic choke. In this case resistance R3 and condenser C5 form the decoupling circuit. Fig. 2 (*c*) incorporates features of both these circuits. Radio-frequency voltages appearing at the valve anode are fed through condenser C7 to the tuned circuit L3, C6 in the grid of the following valve. Really this is a case of tuned anode parallel fed by which name it is often referred to. Fig. 2 (*d*) includes a transformer coupling in the anode circuit. This represents a typical intermediate frequency amplification stage in a superheterodyne receiver, the transformer T having both primary and secondary coils tuned. The coils are inductively coupled to each other to produce a band-pass effect, and the coupling is often made adjustable so as to give the best compromise between selectivity and freedom from side-band cutting which occurs and which worsens the quality if the circuit is made too highly selective.

Stability of the Circuit

The electrodes of a valve are sufficiently close to one another to form very small condensers, and, at high frequencies, the capacities of these small condensers may be sufficiently great to cause trouble if precautions are not taken to avoid the effects they introduce. In the case, for instance, of a triode (Fig. 3) the grid, anode and cathode form three separate condensers. Now, as far as high-frequency voltages are concerned, the capacities CAG and CGC are in parallel with one another, and therefore are additive. One result of the existence of these small condensers is that the impedance of the input circuit is reduced because they introduce damping and loss of selectivity in the tuned grid circuit. Another and more important effect is that CAG forms a path between the anode and grid through which high-frequency impulse can pass back in the reverse direction of the signals, so that energy may be fed back from the anode to the grid. If these feed-back voltages have a component in phase with the grid voltages, the latter may be continually reinforced until the valve is set into a state of continuous oscillation.

It will be noted in the circuit of Fig. 2 the screen of the valve is connected to the high tension supply through a resistance

and a condenser is interposed between the screen and earth. This means that while the screen is kept at a steady positive voltage it is also earthed as far as high-frequency voltages are concerned because condenser C4 (Fig. 2 (*a*)), while barring the way to steady voltages, offers very little obstruction to high-frequency voltages. The capacity of the condenser C4 must

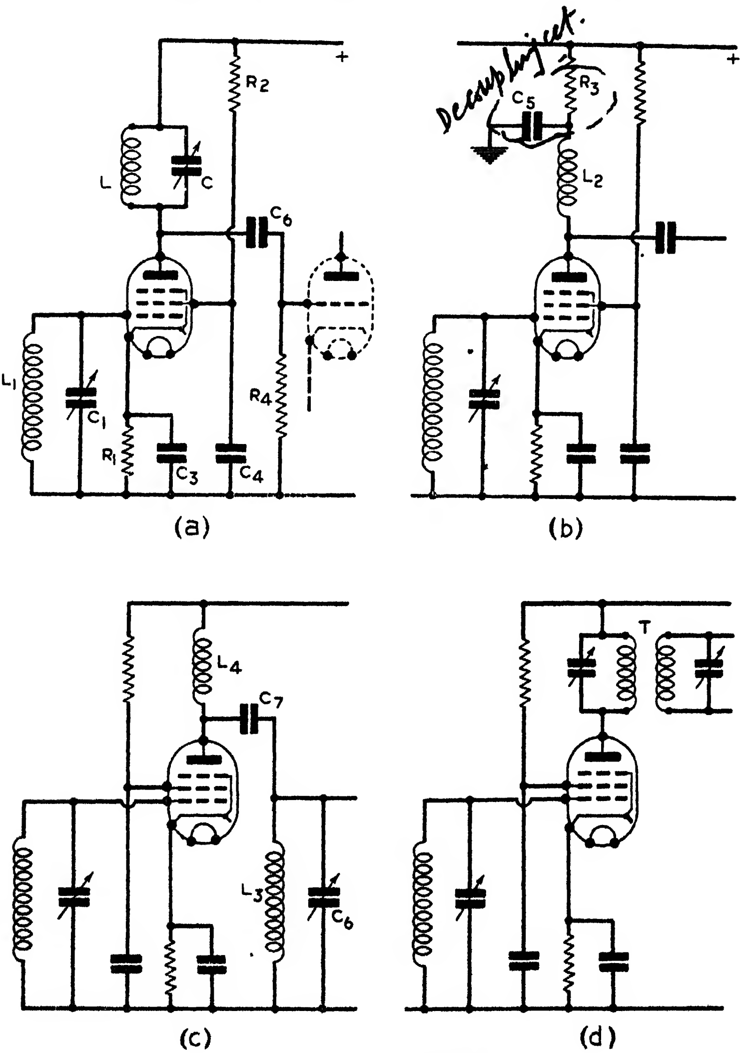


FIG. 2.—H.F. VALVE STAGES.

be large enough to ensure this condition. Something between 0·05 mfd. and 0·2 mfd. is usually suitable for a high-frequency stage. Thus the anode is separated from the grid by an earthed screen so that the capacity between these two electrodes, and the possibility of feed-back, are greatly reduced.

Instability and parasitic oscillations were very difficult to avoid in the early days of radio when only triode valves were available, and where the screening included in modern pentodes was not provided, and all kinds of artifices were resorted to to get over the trouble. The anode circuit was often formed of a bridge including a variable condenser designed to neutralize or balance out the inter-electrode capacity of the valve. Neutrodyne circuits of this kind were widely used, but the trouble was not really satisfactorily overcome until more suitable valves became available.

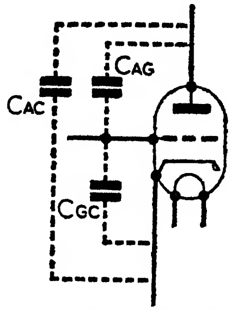


FIG. 3.—SMALL CONDENSERS FORMED BY THE VALVE ELECTRODES.

Thus triodes are never used nowadays for high-frequency amplifiers for reasons which will now be obvious. The construction of the screen grid and high-frequency pentode valve does not, of course, entirely eliminate inter-electrode capacity, but it reduces it to something of the order of $\frac{1}{1000}$ of its magnitude in the case of the triode, so that amplification with far greater stability is possible.

Degree of Amplification

Consistent with stability, it is, of course, desirable to make the amplification as large as possible, and this can be achieved within certain limits by increasing the impedance of the tuned circuit. At its resonant point, the tuned anode circuit behaves like a very high resistance. The frequency to which the circuit tunes depends on the square root of the product of its inductance L and its capacity C. The circuit can be made to tune to the same frequency if L is large and C small, or *vice versa*, as long as the product is the same. The amplification, however, is greater for large values of L and small values of C. It is also greater, the higher the amplification factor (μ) of the valve and the lower the valve impedance. The significance of the last

factor will, perhaps, be obvious, since the tuned circuit and the valve impedance are in series, so that the lower the valve impedance, the greater the proportion of the amplified signal across the tuned circuit.

The amplification factor is, however, a term which is liable to be a little misleading. Supposing, for instance, a screen pentode valve has an amplification factor of 200. This does not mean that the signals are made 200 times as great by passing through the valve. The amplification factor of the valve actually indicates the theoretical gain which would result if the anode load were made infinitely great, which is never possible. In practice, a valve with a μ of 200 would probably give a voltage step-up of about a quarter of this or less according to the actual values of the valve impedance and the anode load.

Selectivity

The selectivity of the high-frequency stage is greatly affected by the design and quality of the coils in the tuned circuit. If the coils have appreciable resistance, damping will be introduced and the tuning will be flattened. Instead of falling away steeply from the point of resonance, the response curve, in the case of a damped circuit, will fall away much more gradually (Fig. 4), so that signals from transmitting stations on wave lengths near to the one it is desired to receive will be amplified to almost the same degree and interference will take place.

The path between the grid and the cathode is in shunt with the tuned grid circuit, and to reduce the effect of this shunt the grid must be maintained at a sufficiently high negative voltage to the cathode. Also for high-frequency voltages the impedance of the valve is in shunt with the tuned anode circuit, so that, other things being equal, a high impedance valve will damp the tuned anode circuit less than one of low impedance. As, however, the impedance is affected by the choice of anode and screen voltages, the desired selectivity will be secured by the correct adjustment of these potentials.

It must also be remembered that the high tension positive and negative terminals though points between which there is a high steady voltage, viz. the full high tension across the circuit, are at the same potential for high-frequency voltages, so that the grid leak R4 of the following valve (Fig. 2*a*) is shunted across the tuned anode circuit and must therefore be of sufficiently

high value or it will introduce damping and loss of selectivity. Condenser C6 must be large enough to offer a relatively low resistance to high frequencies; 0·0003 mfd. is a usual value for C6 and R4 is preferably not less than two or three megohms.

In the case of the untuned choke load with parallel feed circuit of Fig. 2 (*c*), the choke, for reasons previously stated, shunts the following tuned grid circuit comprising coil L3 and condenser C6, so that its impedance must be high compared with the dynamic resistance of this latter circuit, if damping is to be avoided. Now, a high impedance choke needs a large number of turns of wire which introduces resistance, and although the choke is untuned there is its inter-turn capacity between the coils themselves.

The existence of this self-capacity means that the choke has a natural frequency of resonance which cannot be altered and at which its amplification will be abnormally high. To avoid possible distortion in reproduction, this point of resonance must be outside the range of reception.

One of the advantages of high-frequency transformer coupling is that some adjustment of selectivity becomes possible. No attempt is usually made to secure voltage step-up by having a larger number of turns on the secondary than on the primary. The increased stray capacity introduced by so doing offsets any gain in voltage which is theoretically possible, and a 1 : 1 ratio is usual. If the coupling between the coils is reduced, the amplification is made less, but the selectivity is increased, and *vice versa*. Both coils are tuned to secure optimum performance

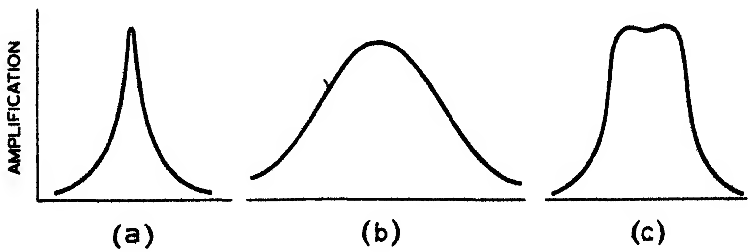


FIG. 4.—H.F. RESPONSE CURVES.

(*a*) Highly selective but distorts at high audio frequencies.
(*b*) Insufficiently selective and liable to permit cross-talk from interference.
(*c*) Indeal band-pass response—a plateau with steep sides.

and when provided, the selectivity control is generally a mechanical one, which permits displacement of the relative positions of the two coils.

Quality of Reproduction.

We will now refer to one or two points in connection with high-frequency amplification which affect the quality of reproduction.

Band-pass Tuning.—So far some emphasis has been laid on the need for a peaked response or sharp tuning to secure freedom from interference. To get good quality speech and music, all the audio frequencies must be amplified and pass through the receiver. This means that the high-frequency valve must pass a band of frequencies on either side of the resonance point without serious loss, otherwise some of the audible tones will be missing. These side-band frequencies are important because if they are suppressed the higher notes will be cut off and the quality will be poor.

We have seen that a tuning response curve like that of Fig. 4 (*b*) is undesirable because it results in flat tuning and poor selectivity. The type of curve in Fig. 4 (*a*) is also undesirable because although it is adequately selective, the side-band frequencies are cut off and the higher notes are poorly reproduced. The ideal curve is that of Fig. 4 (*c*), which gives an almost level response over a band of frequencies covering the audible range and falls off steeply on either side. When a selectivity control is provided, as is often the case in a high-frequency transformer, it becomes possible to narrow or widen the plateau of the curve of Fig. 4 (*c*), and so secure the best compromise between selectivity and good quality.

Amplitude Distortion.—It has been shown in the section on valves that distortion free amplification is only possible when the variations in anode current and grid voltage cover the straight portion of the grid voltage-anode current curve because only over this range will the one be proportional to the other. The grid must always be operated at a sufficiently high negative voltage to prevent the signals ever making it swing positive, which produces grid current and distortion. However, it may not be possible (see Fig. 5 (*a*)) to operate the grid at sufficiently high negative voltage and yet keep it on the straight portion of the curve, when signal impulses cause its potential to fluctuate.

When the signals are of low intensity the grid voltage swing is small, and only the straight part of the curve is used, so that no bad effects are noticed, but when the grid voltage amplitude is large (strong signals) the signals will carry the grid voltage over the bottom bend of the curve so that the grid voltage change produces too small a change in anode current. What this amounts to is that the positive halves of the signal impulses are properly amplified, but the negative halves are not, with the result that distortion is produced. This is what happens in a screen-grid valve where the permissible grid voltage swing is small and load signals easily overload it.

To overcome this trouble, the variable mu valve was evolved. This has a curve of much lower slope; the anode current is reduced much more gradually by applying negative grid bias and a considerable negative voltage on the grid is required to cut it off completely. The result is that a much wider range of signal strength can be handled by the valve without distortion. This will be clear from a comparison of Fig. 5 (*a*) with Fig. 5 (*b*).

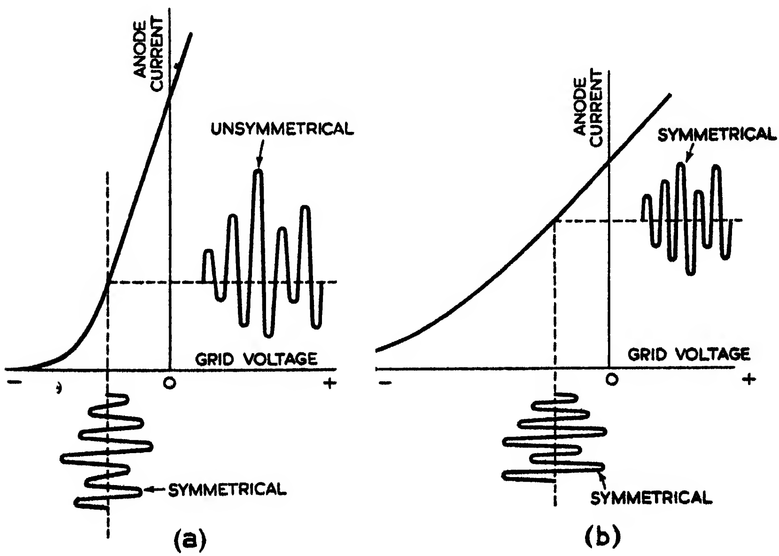


FIG. 5.—VARIATION OF ANODE CURRENT DUE TO GRID VOLTAGE SWING.

(*a*) Unsymmetrical variation in anode current due to grid voltage swing passing on to lower bend of curve, resulting in distortion.

(*b*) Distortion free amplification secured by the use of a variable mu valve having a curve with low slope.

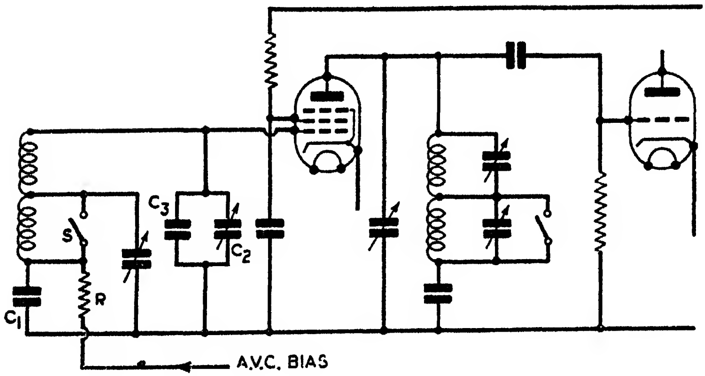


FIG. 6.—H.F. STAGE WITH WAVE BAND SWITCHING AND A.V.C. CONNECTIONS ADDED.

Practical Radio-Frequency Valve Stages

The circuits of Fig. 2 show, as it were, the bare bones of the high-frequency stage. In modern receivers there are several refinements which add to the efficiency of performance. Referring to Fig. 6, it will be seen that the coils of the grid and anode circuits are in two sections, one of which can be shorted by a switch. This enables both the medium and long wave bands to be received. The condensers are also shown with parallel trimmers. Also the grid coils are not earthed, but connected to condenser C1 (0·1 mfd.) and the automatic volume control voltage from a later valve is fed to the top of this condenser through resistance R (0·5 — 1·0 MΩ). The existence of the condenser C1 does not affect the circuit as far as high-frequency voltages are concerned and the coil is still earthed, but it does isolate the coils for steady voltages and enables the A.V.C. voltage to be applied to the grid. Without this condenser the A.V.C. lead would be earthed and rendered ineffective.

In circuits involving anode high-frequency transformers, these are frequently tapped at intermediate points in the winding, and sometimes extra turns can be switched in to vary the selectivity. Some circuits also include a third tuned winding in series with a resistance. As the resistance is reduced, the losses in the third winding increase and the selectivity is made wider.

CHAPTER XIII

THE DETECTOR STAGE

THE transmission of speech and music across space necessitates the use of radio-frequency waves as carriers of the audible frequencies. In the transmitter, oscillation of radio-frequency are generated by suitable valve circuits and are conducted to a radiating aerial, whence they are sent out into space as electric and magnetic fields. The speech and music frequencies with which the receiving apparatus is eventually solely concerned are impressed or superimposed on the radio-frequency oscillations at the transmitter by the process of modulation; when these modulated radio-frequency waves are received, they are usually—though not necessarily—first amplified to increase their strength without altering their character.

The radio-frequency carrier may be altered to one of lower frequency—as in the case of the superhet receiver—for reasons which are explained in the chapter on the superheterodyne receiver, but at some point in the receiver circuit the audible components in the modulated radio-frequency waves have to be separated from the carrier by a process which is really the reverse of that which takes place at the transmitter and is known, therefore, as demodulation or detection.

Demodulation

The necessity for demodulation will be almost obvious. If the amplified radio-frequency signals were applied to the sound reproducer without demodulation, no response at all would be obtained. The frequency of the individual oscillations is so high that no mechanical moving device could possibly respond to them. The diaphragm of the loudspeaker can only respond to the changes in the average values of the current when these take place at audible frequencies.

Basic Principles of Detection

Now, in a modulated radio frequency carrier, there is no change in the average value of the current since the waveform is symmetrical and fluctuates to the same extent on either side of its mean value. The effect of the positive half of the wave is exactly equal and opposite to that of the negative half. The detector valve must, therefore, convert these variations in the modulated carrier wave into unidirectional impulses, so that the effect of the changes in current in the sound reproducer do not cancel each other. The modulation component can then bring about changes in the average current through the loudspeaker which enable the original sounds at the transmitting end to be reproduced.

Though the term detection has become well established by usage, it is clear that demodulation more clearly expresses what happens in the detector valve stage. It will be clear, therefore, that there is no essential difference between "detection" so called and alternate current rectification. The detector valve is really a special kind of rectifier which has to deal with modulated, high frequency, alternating currents.

The function and essential nature of the detector valve stage will thus be clear. Besides changing the alternating signals into unidirectional impulses, the detector valve stage has another and important function to perform, *viz.*, to separate from one another the two superimposed currents, one of high or radio frequency which is now no longer required, and one of low or audible frequency which will finally be fed into the loudspeaker.

Frequency Separation

This frequency separation is carried out in the circuit associated with the detector valve and not in the valve itself. Current variations of both radio and audible frequency will appear in the output circuit. If the components included in the output circuit are chosen so as to present a low impedance to signals of low frequency, but a very high impedance to signals of radio frequency, it is possible to separate these two components and ensure that only the low frequency components are passed on to the next valve. By the use of suitable shunting circuits, the radio-frequency impulses can be selected out and by-passed away from the anode load. It is essential to see that separation of the radio-frequency component in the detector stage is complete

and that no signals of high frequency are allowed to find their way into the next valve. Otherwise, if radio-frequency components get mixed up with the speech and music signals in the low-frequency amplifier stage, distortion and instability will result.

If a small condenser is connected between anode and cathode of the detector valve, this will provide a low impedance path for high frequency impulses which will be by-passed from the anode circuit. If sufficiently low in capacitance this condenser will offer a high impedance to the low frequency signals and will have no effect on them since it will be practically an open circuit

Feed Back

It should be noted that, where some degree of amplification takes place in the detector valve, as it does in the case of triodes, whose function in such cases will be described later, the radio frequency components, by-passed from the anode circuit of the detector valve, have the same high frequency as the incoming modulated carrier. If they are fed back to the grid circuit with the correct phase relationship, the incoming modulated carrier will be reinforced by the process known as positive feed back. To a very limited degree this secures some gain in signal strength, but also, what is more important, improved selectivity. Reaction, as positive feed back is called, was used considerably in the early days of radio, when every possible device had to be called upon to assist in boosting up the amplification as much as possible, but the great improvements made since in valve design have made reaction, as a means of increasing amplification, largely unnecessary. Consequently, in view of its disadvantage in that, if not carefully controlled, feed back may build up and produce distortion through instability, if not continuous oscillation, reaction is now seldom used except in very low gain receivers or cases where improvement in selectivity is required.

Diode Detectors

The way in which a diode valve detector functions will be clear from the exeplanation previously given in the chapter on valves. Unlike triode detectors, the diode, of course, cannot amplify, but its low resistance in the direction of current flow makes it particularly suitable where freedom from distortion is

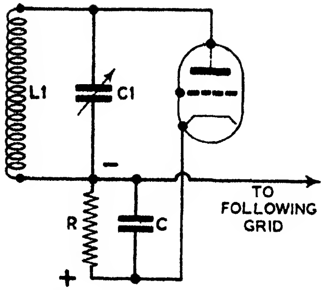


FIG. 1.—DIODE DETECTION.

desired. Fig. 1 shows the basic circuit of a half-wave diode detector. Rectified signals appear across the resistance R and the high frequency components are shunted through the condenser C.

Instead of a single diode, a double diode is often used. The two anodes of a double diode valve may be connected together for half-wave rectification with corresponding reduction in valve resistance or, as is frequently the case, they may be used to give full-wave rectification and included in the same bulb with a triode or pentode, so that this section of the valve can perform the function of amplifying the low frequency signals. Such valves are known as double diode triodes (Fig. 2) or double diode pentodes. Diode detectors are widely used in superhet receivers.

Referring now to the basic circuit of Fig. 1, it will be noted that there is no applied voltage in the anode circuit of the diode, so that, when no signals are being received, the anode may be considered as being at zero potential with reference to the cathode and corresponds then to the point 0 in Fig. 3. We shall assume this condition, though in point of fact, there is a small flow of current through resistance R and the anode is slightly negative to the cathode. When the tuned grid circuit receives signals from the previous stage, the first half of the signal cycle will drive the anode positive and current will pass through the valve to charge the condenser to the polarity shown in Fig. 1.

If the resistance R were absent, the charge acquired by condenser C would bias the anode negatively, so that the next positive half of the signal would produce a smaller change in anode current. Therefore the resistance R (and condenser C) must have suitable values so that the circuit is restored to its original con-

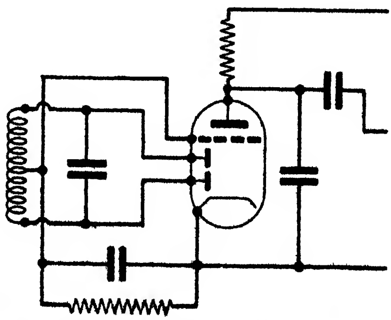


FIG. 2.—DOUBLE DIODE TRIODE CIRCUIT GIVING FULL WAVE DETECTION.

dition. Condenser C is designed to by-pass the high frequencies, but if it is made too large, it will pass some of the high audio frequencies as well and there will be an upper note cut-off.

The resistance R must be low enough in value to allow the acquired charge, due to the signal impulse, to leak away sufficiently to avoid the distortion previously referred to, so that the rectified low frequency output is a true copy of the modulation component of the incoming signals. On the other hand, if R is made too small it will impose excessive damping on the tuned circuit and both amplification and selectivity will be reduced. Usual values are R = 1 MΩ and C = 0·0001 mfd.

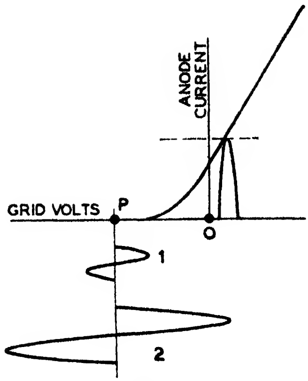


FIG. 3.—CONDITIONS OF OPERATION OF A DIODE DETECTOR.

Effect of Biasing the Diode

If a steady negative voltage is applied to the diode anode, it is obvious that the anode cannot become positive nor can appreciable current pass through the valve until the signal voltage exceeds the bias voltage in the positive direction. Thus in Fig. 3, suppose a steady negative bias represented by OP is applied to the diode. This will cut off the current through the valve completely. An incoming signal represented by the alternation 1 produces no current through the valve at all since the anode never becomes positive (or even reaches the bottom end of the curve). A signal of larger amplitude, such as that represented by the alternation 2, makes the anode positive and causes current to flow throughout a small part of the signal cycle. The effect of the negative anode bias, therefore, is to cut off current for all signals except those exceeding a certain minimum amplitude. This principle is utilized in delayed automatic volume control in which the automatic volume control does not come into action until the signals exceed a certain minimum strength. This avoids the production of background noise which would occur if excessive amplification were applied to very weak signals.

Diode Operating Conditions

Fig. 4 shows the use of a double diode detector corresponding to the single diode of Fig. 1.

So far it has been assumed that a steady current passes through the diode and Fig. 1 is based on this assumption, so that this curve really only represents static conditions. During use in a receiver, both voltage and current fluctuate rapidly. When signals are being received, the voltage across resistance R (Fig. 1) is proportional to the current through the valve, *viz.*, to the depth of modulation or intensity of the received signal. It has been explained in the case of triodes how a series of anode voltage/anode current curves, each for a different value of grid bias, can be employed to deduce a suitable value for the anode load. In a somewhat similar way, a series of curves relating diode current against negative anode bias voltage, for different values of high-frequency input signal, enable load lines to be constructed from which suitable values of the diode load can be deduced.

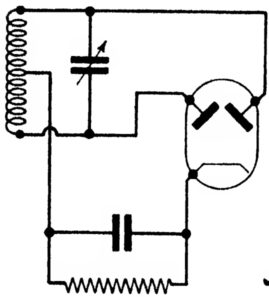


Fig. 4—Full Wave Diode Detection

A common method of coupling the diode output to the first low-frequency amplifier valve is that shown in Fig. 5. R1 is a high-frequency stopper and C1 a high-frequency by-pass condenser, this combination providing an additional filter for the carrier frequencies. The low-frequency coupling condenser is C2 and R3 is the grid leak of the following valve.

Triode Detectors—Anode Bend Detection

There are two common methods in use by means of which triodes carry out the function of the detector valves, *viz.*, anode bend detection and grid detection.

It has already been explained that when a triode valve operates as an amplifier, the linear or straight portion of the characteristic curve only must be covered by the grid voltage swing, otherwise distortion will take place.

Now, with anode bend detection, which is also known by several other names, such as anode or plate detection, or anode circuit detection, the grid is negatively biased; in a battery set,

by increasing the voltage of the grid bias battery, or in a mains set, by the use of a cathode bias resistor of suitable value, so that when no signals are being received the anode current is small and the valve is operating near the bottom bend of the grid voltage/anode current curve.

Thus in Fig. 6, suppose the grid is biased by a negative voltage represented by OX, so that in the no-signal state the working point is at P on the curve. Suppose now a single cycle impulse is given to the grid. This is shown as a symmetrical alternation about the mean voltage of the grid. The positive half of the cycle carries the working point up the curve to R, representing an increase in anode current equal to BC. The negative half

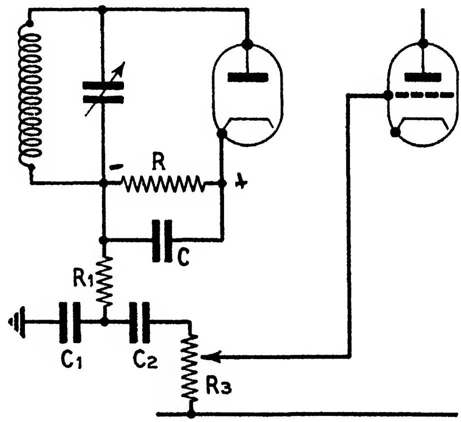


FIG. 5.—A COMMON METHOD OF COUPLING THE DIODE DETECTION OUTPUT TO THE FOLLOWING VALVE.

R_1 is a high-frequency stopper; C_1 a high-frequency by-pass condenser; C_2 a low-frequency coupling condenser; and R_3 the grid leak of the following valve.

cycle carries the working point down to S, representing a decrease in anode current equal to BA. Owing to the decreasing slope of the curve towards its lower end, the increase in anode current due to one half cycle of the grid voltage is greater than the decrease due to the other half cycle, so that the average anode current is increased. Modulated radio-frequency oscillations received by the grid circuit are thus rectified.

Anode bend rectification does not take energy from the oscillatory grid circuit, so that it imposes no damping in the tuned circuit and the degree of selectivity obtainable with it is high. It is rather less sensitive than grid detection and is frequently credited with a lower quality of reception. The advantages referred to are, of course, dependent on the valve being biased

with sufficiently high negative grid voltage, because the path between the grid and cathode in the valve is a shunt to the tuned grid circuit, so that high selectivity can only be secured if the impedance of this path is high enough to minimize damping.

It will also be clear from a further examination of Fig. 6 that the greater the grid voltage amplitude, the more complete the rectification, i.e. the anode bend detector is insensitive to weak input signals.

Grid Detection

The earliest use of the triode as a detector was that known as grid detection or leaky grid rectification. The simplest form of circuit operating in this way is shown in Fig. 7, where two alternative arrangements are shown. The condenser C has a capacitance of the order of 0·0003 mfd. and the resistance R is usually within the range of 0·5 — 4MΩ. This arrangement can be looked upon as a combination of a diode detector and a low frequency amplifier in which the two functions are performed by the same valve. The grid and filament can be regarded as a diode system, the parallel connected condenser C and resistance R of the circuit of Fig. 7 (a) serving the same purpose as the similar combination in the circuit of Fig. 1.

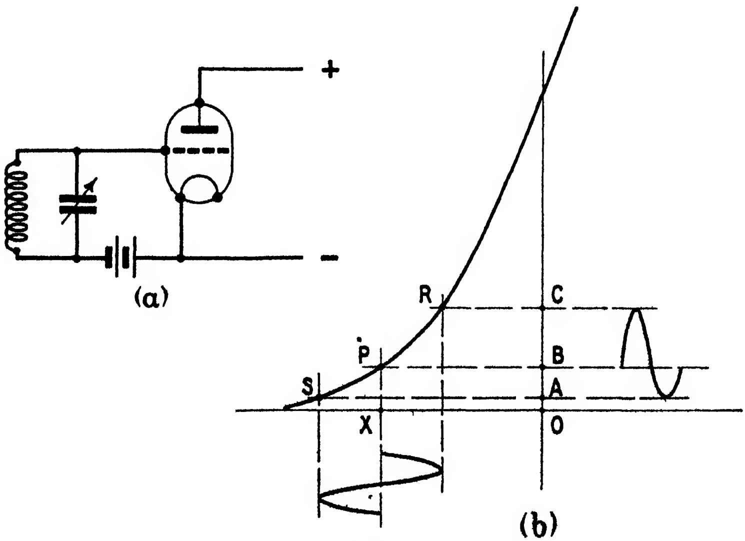


Fig. 6.—Anode Bend Detection.

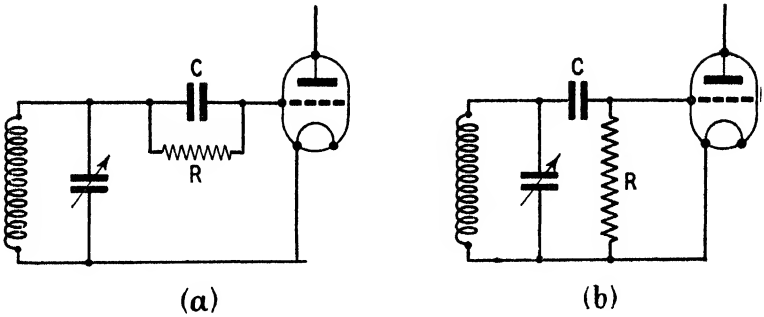


FIG. 7.—GRID LEAK DETECTION.

In the circuit of Fig. 7 (a), the low-frequency voltage changes which occur across this resistance are not passed on to a following valve, but are impressed on the grid to control the electron stream in the triode system and provide amplification of the rectified, alternating signals. We have, therefore, a combination of two valves in the one bulb, the grid acting partly as an anode for the purpose of rectification and partly as a control grid for the triode of a low frequency amplifier.

An alternative method of connecting the resistance R is to take it back to the cathode circuit as in Fig. 7 (b). This circuit functions in exactly the same way except that it imposes more damping on the tuned grid circuit.

The action of a triode in providing grid rectification can be explained in another way, since it utilizes the existence of grid current.

It has been shown in the chapter on valves that when the grid of a triode is slightly positive—or even at a very low negative voltage—grid current may be produced through some of the electrons in the stream from cathode to anode entering the grid and returning to the cathode through the grid leak. As the grid is made more positive this grid current increases.

Function of Grid Detection

The process of grid detection utilizes this grid current in such a way as to secure rectification of the high-frequency oscillations in the tuned grid circuit.

When no signals are being received, some electrons enter the grid and pass through resistance R, Fig. 7 (b). This high

resistance does not offer a very easy path so that a negative charge which cannot leak away completely is built up on condenser C and a state of equilibrium is soon established in which the grid acquires a negative bias. The magnitude of this bias is, of course, determined by the value of the resistance R.

Now when signals are being received, the oscillations in the tuned grid circuit tend to make the grid condenser C alternately positive and negative. During the positive half cycle, when the voltage of the grid condenser is made less negative, electrons are drawn from the valve and grid current flows, making the condenser still more negative. During the following and negative half cycle of the signal voltage, the effect is reversed and the negative voltage, already acquired by condenser C, makes it more negative than it would otherwise have been if no grid current had passed. The positive half cycles of the signal frequencies alone are, therefore, effective in producing grid current which increases the negative grid voltage and reduces the anode current.

The action of resistance R is to restore the original grid condition and establish a mean bias potential on the grid. The effect of grid rectification is, therefore, to reduce the average value of the anode current. Since the rectified grid voltages result in correspondingly greater changes in anode current, the valve amplifies as well as rectifies.

We have seen now the distinctive difference between anode bend and grid rectification. The former produces an increase in the average value of the anode current and the latter a decrease when signals are tuned in. It is easy, therefore, to see which form of detection is being used by including a current meter in the valve anode circuit and noting the direction of the change in anode current.

Component Valves

Unsuitable choice of values for the grid leak and condenser may result in considerable distortion being produced especially with weak signals, since anode bend rectification and grid rectification may take place at the same time and produce opposite effects. Fig. 8 shows the equivalent circuit which is connected across the tuned grid circuit in the case of grid detector. The impedance of the circuit shown in Fig. 8 must be large, otherwise it will seriously damp the tuning. In addition, the voltage V2

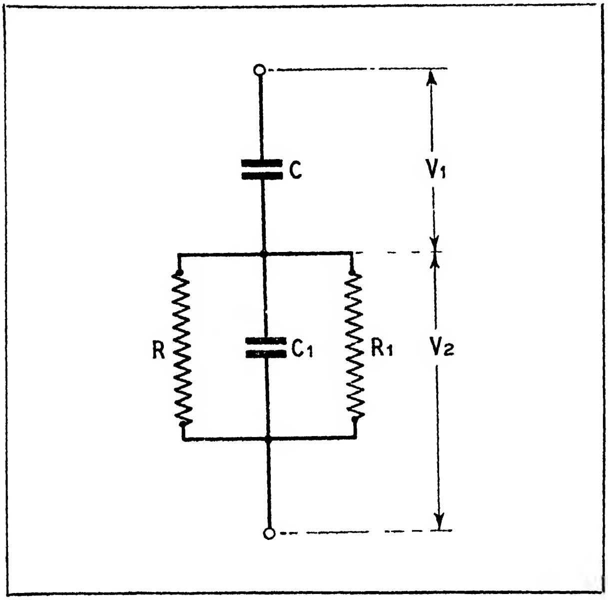


FIG. 8.—EQUIVALENT LOADING OF TUNED GRID CIRCUIT IN A GRID DETECTION STAGE.

C = grid condenser, R = grid leak resistance, C_1 = interelectrode valve capacitance, R_1 = impedance of grid–cathode path of valve.

applied to the valve grid must be a large portion of the whole voltage if the arrangement is to be sensitive, so that the condenser C should be several times larger than the interelectrode capacitance of the valve.

On the other hand, the value of CR on the time constant of the grid circuit must be low enough to enable the grid of the valve to be restored to its equilibrium voltage between the signal impulses, otherwise frequency distortion will be produced. It is a matter of compromise, therefore, in selecting the grid components, between sensitivity on the one hand, and freedom from distortion and ability to handle heavily modulated signals on the other.

Power Grid Detection

Consequently, before the present general adoption of the diode detector, a method of rectification known as power grid detection was largely used. This functions in exactly the same way but the grid leak is made much smaller (0·25MΩ) and the

grid condenser about 0·0001mfd. Power grid detection thus sacrifices sensitivity to handle power. It has the disadvantage of drawing power from the preceding circuit and, in consequence, reduces the circuit selectivity.

Pentodes

Pentode valves have also been employed in the detector stage, usually for grid rectification, though the general result of their use is to produce a lower level in quality of reproduction.

CHAPTER XIV

THE SUPERHETERODYNE RECEIVER

AMONG domestic receiver sets, the superheterodyne is, without doubt, the most important because the principles it involves are incorporated into the great majority of present-day sets and certainly in all those which include high-frequency amplification. The rather formidable name sometimes implies a certain amount of unintelligible mystery to the layman though the principles and reasons for their adoption are quite easily understood. Let us look first at the title itself, sometimes referred to in its full regalia as supersonic heterodyne. Heterodyne really means "another source of power" and supersonic means "above the range of hearing."

These definitions may seem rather far removed from the idea of reception of radio signals, but the combined title obviously means, by inference, that reception is carried out through the assistance of another source of power operating at frequencies above the range of audibility. To put it another way, the reception of the speech and music sent out by a distant transmitter is made possible by the help of a second or local oscillator in the receiver set. We shall now see how this arrangement functions and understand its important outstanding advantages. First of all it may be asked why is this arrangement necessary at all and why is it preferable to a straightforward amplifier. The answer is that it provides the best means of simplifying the problem of radio-frequency amplification; but, as we shall see later, the superhet receiver has other merits.

Weak signals need to be amplified before they can operate the valve circuits in the receiver, and although this is relatively easy at low frequencies it becomes increasingly difficult to provide efficient and stable amplification at very high frequencies (short wavelengths). It is almost common knowledge that short-wave receivers require a special technique of their own and particular care in design if they are to operate satisfactorily. Great

attention has to be paid in their wiring to eliminate stray capacities which might be neglected in a low-frequency amplifier. In the early days of radio, when many of the modern artifices were not available, the problem of producing a satisfactory radio-frequency amplifier was a real headache to set makers and all sorts of devices were resorted to secure stability and freedom from parasitic oscillations. We can assume, therefore, that any process which enables amplification to be carried out at lower frequencies will be advantageous ; and this is one of the things which the superhet receiver does. The principles of this type of receiver are quite old—a circuit was published in the press in 1923—yet it is only relatively recently that its use has found wide application.

General Principles

To understand the principles of its operation, we must first drop the old habit of thinking of radio signals in terms of wavelengths and refer to them in terms of the frequency of oscillation, remembering that short wavelengths correspond to high frequencies and *vice-versa*. Continuous waves of radio frequency could not produce any audible sound in the loudspeaker of a receiver. Their frequency is so high that no diaphragm could move fast enough to vibrate in step with them and, in any case, the frequency is far above the limit to which the ear can respond. When continuous waves sent out by a distant transmitter are being received the loud speaker merely emits a click at the beginning of the wave train and another click as soon as the wave train terminates. In order to transmit audible speech or music, the continuous waves have to be modulated at the transmitter and the low-frequency signals are superimposed on the radio-frequency waves which act as the carrier.

If, however, another transmitter is sending out continuous radio waves of a different frequency still far above the range of hearing, the two sets of waves may interfere and produce other frequencies some of which may be audible. This principle of interference between two sources of nearly the same frequency is very important. It is not difficult to experience a parallel effect with sound waves which enables the principle to be more easily understood. When two notes close together on the lower register of a church organ are sounded at the same time, a peculiar throbbing effect is noticeable and may even be uncom-

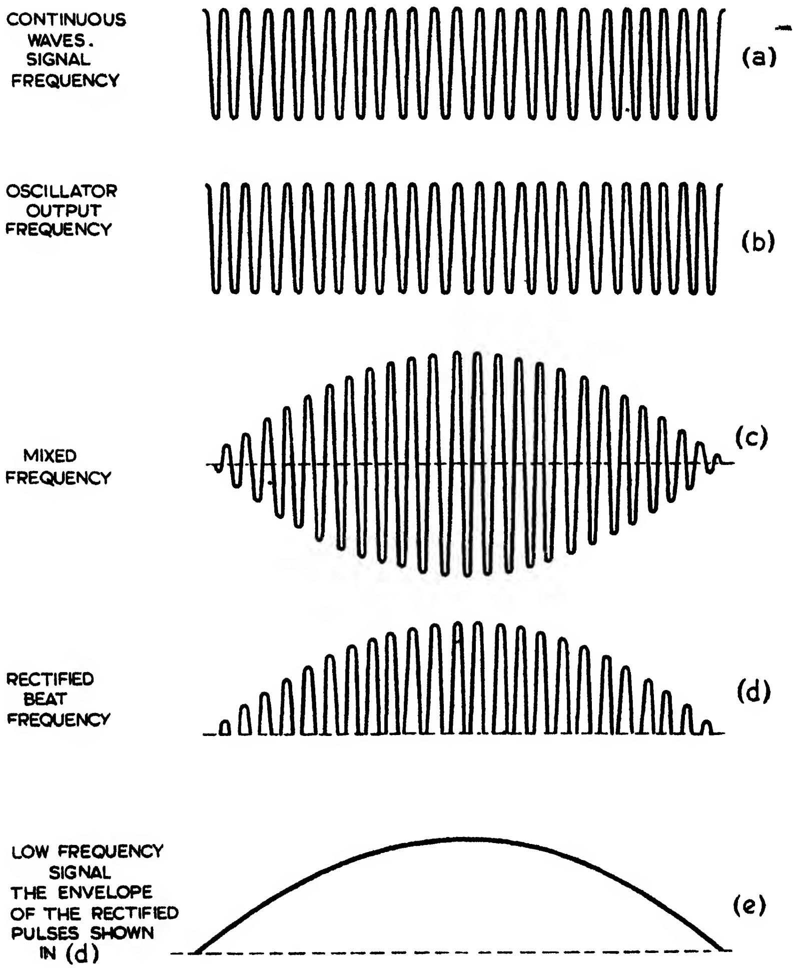


FIG. 1.—DIAGRAMMATIC REPRESENTATION OF THE HETERODYNE PRINCIPLE FOR CONTINUOUS (UNMODULATED) RADIO WAVES.

fortable to the ear. This pulsating is due to sound waves which have a frequency equal to the difference of the frequencies of the two individual notes and the pulses are slow enough for each separate vibration to be counted. The beats so formed are known as difference tones. This principle of interference between waves of nearly the same frequency applies also to radio waves and two oscillators operating at nearly the same frequency

will give rise to a beat frequency which is the difference of the two transmitter frequencies. It may or may not be low enough to be audible.

We can look at this principle in another way. Suppose two alternating currents of the same frequency are fed into the same circuit. The resulting current will also be alternating and its value will depend on the phase angle between the separate currents. If the two are in phase, they will be always assisting one another and the current will be large; if they are originally out of phase, they will oppose one another and the resulting current will be small. If, however, the two component currents are of different frequencies, the resulting current will fluctuate widely since the phase angle will be continually changing; sometimes the currents will be in phase and help one another, making the resultant current large; at other times they will be exactly out of phase and oppose one another, giving a small resultant current. Thus, since all intermediate stages between these extremes will occur, a series of peaks or beats will be produced. This is true for alternating currents of all frequencies, radio or otherwise, and is made clear in Fig. 1. The continuous waves shown in Fig. 1(a) are slightly different in frequency from those due to a second source, Fig. 1(b). The two, when superimposed, give rise to the wave form of Fig. 1(c). When rectified this gives a low frequency, one pulse of which is shown in Fig. 1(e).

When the sensitivity of a straight receiver is turned up to a maximum, the set may become unstable and oscillate, *i.e.*, generate radio-frequency waves. If there are no outside transmitters working, these oscillations will, of course, be inaudible and it will be impossible to tell by listening whether the set is oscillating or not. But if there are some outside transmitters working, as there nearly always will be, then one of these may beat with the oscillations in the receiver and the set will "howl," at least at some portions of the tuning scale and the pitch of the note will alter as the tuning condenser is adjusted.

Now a superhet broadcast receiver is really a transmitter as well as a receiver except that the generated oscillations are not allowed to get outside the set. The oscillations generated in one section of the set are injected into the valve circuits of the receiver and mix with the high-frequency incoming signals, producing a beat note or waves of much lower frequency. These

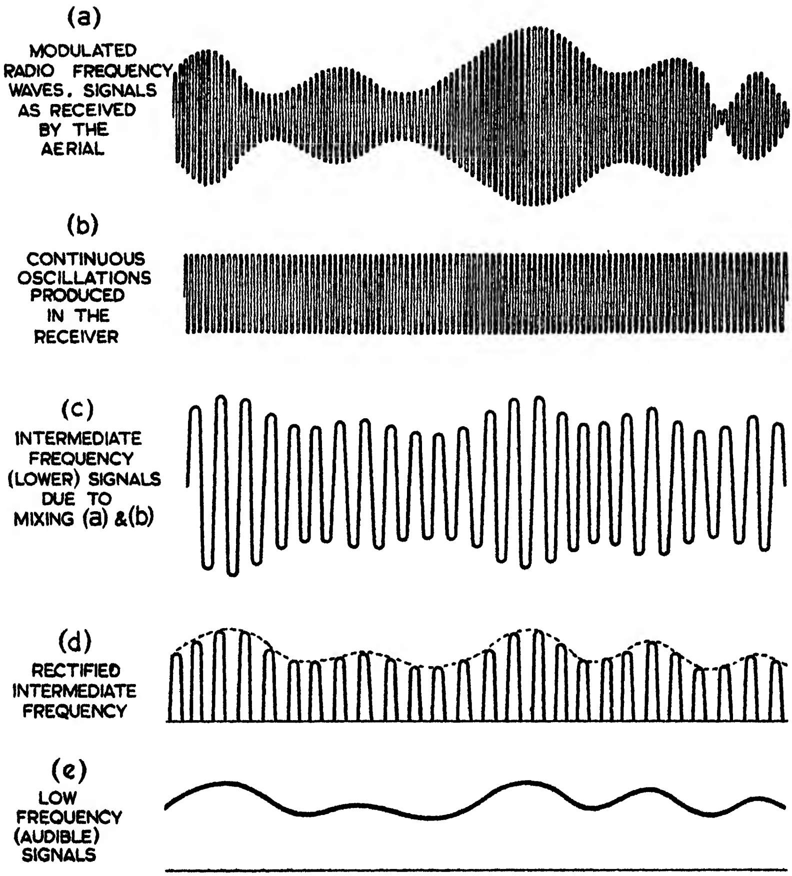


FIG. 2.—DIAGRAMMATIC REPRESENTATION OF PRINCIPLE OF SUPERHETERODYNE RECEPTION OF MODULATED R.F. SIGNALS.

resultant waves, though of lower frequency, are still of high frequency in the sense that they are above the limits of hearing. The advantages of this frequency conversion will not, therefore, be immediately obvious, but we shall see later that its results are very important. From what has been previously stated it will, however, be clear that being of lower frequency these signals will be much easier to amplify. At the moment it is only necessary to remember that in the case of modulated waves, the beat frequency also carries the modulation of the incoming radio waves. This is shown diagrammatically in Fig. 2.

Beat Frequencies

We will now consider the effect of varying the frequency of the locally generated oscillations, when receiving radio signals from a distant transmitter which we will assume has a carrier frequency of 1,000 kilocycles (wavelength 300 metres). If the local oscillator in the receiver is also tuned to 1,000 kilocycles, the two frequencies will be the same and no beat note will be produced. If the local oscillator is tuned to generate oscillations of 990 kc/s. frequency, then a beat note of 1,000 − 990 kc/s. will be produced. Other frequencies will also be produced at the same time, but this is a prominent one and the only one we will consider at the moment. Similarly, if the local oscillator frequency is 1,010 kc/s. a beat frequency of 10 kc/s. will also be produced since 1,010 − 1,000 = 10 kc/s. In exactly the same way, beat frequencies would be produced if the local oscillator generates oscillations of constant frequency and the incoming radio waves change in frequency. It should be noted that there are two signal frequencies, one above and one below that of the local oscillator, which will produce the same beat note.

Supersonic Frequencies

In the example just quoted, the beat note is just audible. Consequently it would be useless for the reception of speech or music since it would confuse and spoil the reception completely. If instead of broadcast radio, signals are being received as telegraphic code messages, then the local oscillator will be tuned to a frequency such that the beat note is audible, and since it is then of low frequency, if too weak to be put straight into the sound reproducer, can be amplified in a straightforward low-frequency amplifier. The operator at the receiving station can alter the pitch of the note by adjusting the frequency of the oscillator so that by this means he is able to separate it at will from other interference which may be present.

The upper limit of hearing varies with different individuals, but it can generally be assumed that anything above 20 kc/s. is beyond hearing. Frequencies above this range are called supersonic and for broadcast reception the local oscillations must be such that the beat frequency is above the audible limit. Under these conditions the beat note is called the intermediate frequency; it carries the modulation of the original incoming

signals and can be amplified by valve circuits. It does not matter in principle whether the oscillator frequency is higher or lower than the incoming carrier, as it is only the difference of the two which determines the intermediate frequency. There are, however, reasons which will be referred to later why the oscillator frequency is chosen to be the higher of the two.

Selectivity

When a receiver is situated relatively close to a transmitter the amplification required is not usually very high, and little difficulty is experienced from interference from more distant stations ; but as the sensitivity of the set is made greater in order to extend its range in distance it becomes increasingly difficult in view of the large number of stations transmitting at the same time, to get reception from one without interference or background from some other station. An important factor of a sensitive receiver is, therefore, its selectivity or ability to separate, without overlapping, the transmissions of two stations broadcasting on fairly new wavelengths. This is known as adjacent channel selectivity.

In a straight set using high-frequency amplification, tuned filter circuits are used to accept the wanted signals and reject the unwanted ones ; but filter circuits do not cut off their acceptance or rejection at one definite point, which is what is really required to separate two such transmissions effectively. Both the wanted and the unwanted signals are attenuated or reduced in strength, the latter more than the former, so that only incomplete separation is secured by this means and always with the loss of signal strength. Now the superhet receiver is very much more efficient in this respect. The much greater selectivity which is possible by its use can be best understood by an example.

Assume that there are two transmitters, one broadcasting on a 2,000 kc/s. frequency and another on 2,100 kc/s. frequency. Now the frequency separation of these two stations is obviously 100 kc/s., *i.e.*, a relative frequency separation of about 5 per cent. Now suppose that these stations are being heterodyned by a local frequency of 2,300 kc/s. In the first case the intermediate frequency is 300 kc/s. ; in the second it is 200 kc/s. The difference is still 100 kc/s., but the difference now is 50 per cent. of the lower of the two, so that the relative frequency separation

is about 10 times as great, and the selectivity of the receiver has been greatly increased. The signals due to an interfering station are thus more easily rejected and tuned out and there is much less chance of their upsetting the reception.

Though this example serves to illustrate the reason for the increased selectivity of the superhet receiver it might be assumed from it that the intermediate frequency is variable. In actual receivers the intermediate frequency is kept constant for very good reasons, which will be referred to later.

The superheterodyne receiver thus has to handle alternating currents of four different frequencies :—

1. The radio-frequency signals which enter the aerial system.
2. The locally generated oscillations.
3. The intermediate frequency signals resulting from mixing 1 and 2.
4. The low-frequency or audible signals which exist first as the modulation component of 1 and 3 and are finally separated in the second detector stage.

There are also two detectors. The first detector separates the beat frequency just in the same way as the detector in a straight set separates the low-frequency component or modulation from the radio-frequency modulated carrier and the second detector performs the normal function of separating the low-frequency signals from the modulated intermediate frequency.

Other Advantages

Besides possessing the advantages of simpler amplifying circuits on account of the lower intermediate frequency and greater selectivity than a straight set, the superhet receiver has other points of interest. In a straight set, the resonant circuits are tuned by variable condensers since reception has to be carried on at any desired point over a band of wavelengths and the condenser capacity has to be adjusted for reception at each part of the scale. Such a tuned circuit is most efficient at one particular point of this waveband and reception is better at this point than at other points of the scale. Therefore, over the greater portion of the scale the tuned circuit in a straight receiver is not working at its maximum efficiency and corrective devices have to be introduced to even up the response, a procedure which complicates set construction.

Now, in the superhet receiver, the intermediate frequency is kept constant. The tuning control alters the oscillator frequency and keeps it in step with the signal frequency so that the difference between the two is the same over the whole scale. This means that the intermediate frequency amplifier has to amplify one radio frequency only and not a wide band of frequencies as in the case of a straight set. Consequently, the tuned circuits will have fixed condensers and be designed to give their best performance at or near the fixed intermediate frequency. Thus the whole circuit becomes much more efficient as a radio-frequency amplifier. In addition there are fewer tuning controls. In a straight set every tuned circuit needs a variable condenser so that the costs of production are increased.

Second Channel Interference

With the previous facts in mind it will have been noticed that for a given oscillator frequency there are two signal frequencies which will produce the required intermediate frequency. Thus with a set designed for an intermediate frequency of 100 kc/s. and with the oscillator tuned to a frequency of, say, 2,000 kc/s., incoming signals of 2,100 kc/s. and 1,900 kc/s. will both produce the same 100 kc/s. intermediate frequency. These two signal sources are spaced equally on opposite sides of the oscillator frequency. If it is desired to tune into one of these transmitters some means must obviously be devised for rejecting or getting rid of the other one, which is known as second channel interference. Separation of these two signal frequencies is carried out, either by employing a tuned aerial system, or a stage of signal frequency amplification, or both, so that the intruding signals can be prevented from reaching the mixer stage. The tuning controls of these circuits will be coupled to the oscillator tuning condenser so that the aerial system presents a high impedance to signals of second channel frequency over the whole scale which the receiver covers.

Frequency Changing without Rectification

Previously it was stated that rectification was necessary for producing the intermediate frequency signals. This statement is not precisely true in respect of the modern type of receiver and needs modification by reason of the action of modern multi-grid mixer valves. Formerly the frequency changer was called

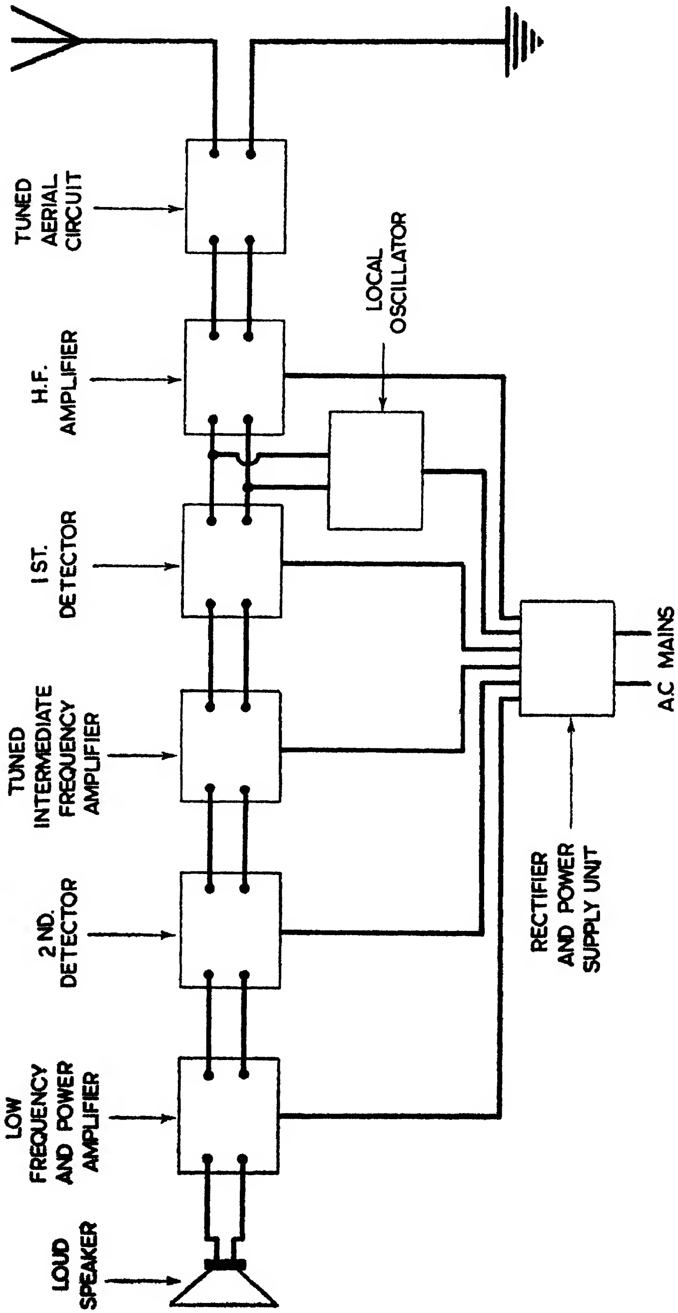


FIG. 3.—BLOCK DIAGRAM OF MAINS OPERATED SUPERHETERODYNE RECEIVER.

the first detector, since rectification was a necessary function of its operation. A mixer valve is one in which the signal frequencies are received on one grid and the local oscillations injected on to one of the auxiliary grids, the intermediate frequency signals being one of those—the one in which we are primarily interested—which appears in the anode circuit. The fundamental prinicple is that shown in Fig. 3. In a frequency changer valve, the oscillations are generated and mixed with the incoming signals.

Frequency Conversion

There are three general methods employed for converting the signal frequency to the lower intermediate frequency. These arrangements are similar, in so far as they all use a valve as a means of mixing the signal and oscillator frequencies and variations in the anode current of this valve produce a voltage across a tuned circuit in its anode circuit. Voltages of other frequencies are produced, but these are rejected by the tuned circuit. The different methods of frequency conversion differ in the types of valves they use and the way in which the component voltages are applied to the mixer valve. A valve which performs the dual functions of oscillator and mixer in the same bulb, is called a frequency changer.

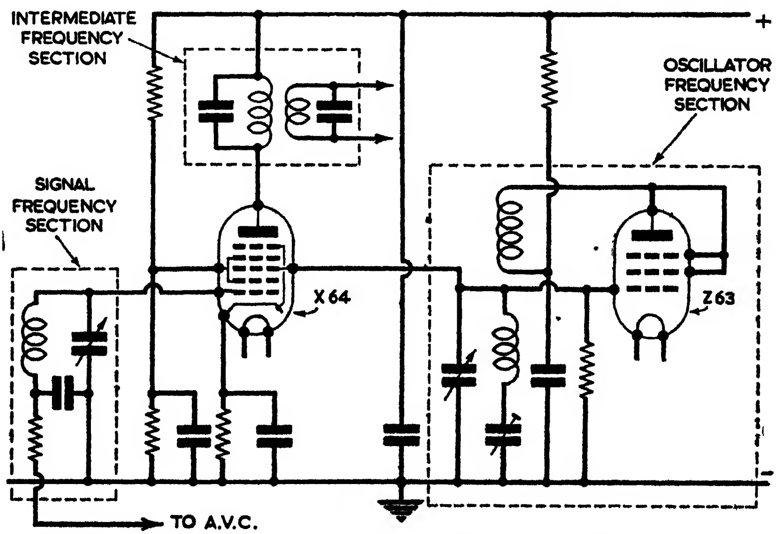


FIG. 4.—FREQUENCY CONVERSION WITH SEPARATE TETRODE OSCILLATOR AND HEPTODE MIXER VALVE.

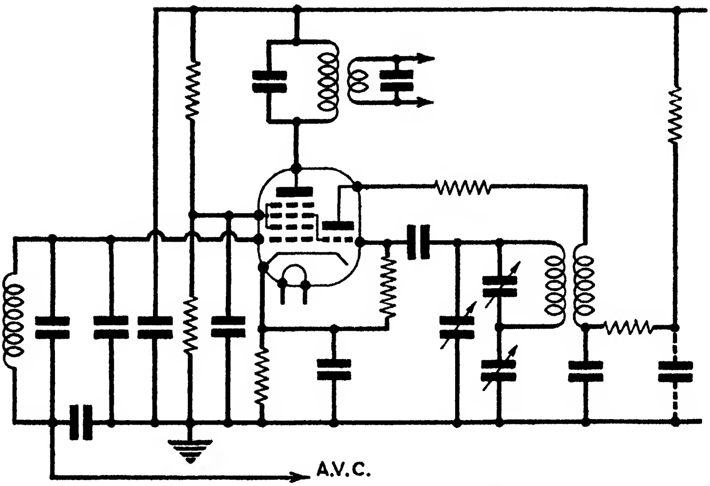


FIG. 5.—TRIODE HEXODE VALVE USED AS A FREQUENCY CHANGER.
The electrical systems of the mixer valve and oscillator valve are in the same bulb.

Before valves designed specially as frequency converters were made available, the mixer valve was either a triode, tetrode or pentode and the oscillator and signal voltages were applied to the same grid of the mixer valve. Either capacity or inductive coupling was employed to couple the mixer and oscillator circuits. The second method employs a separate oscillator valve with its grid connected to one of the grids of a specially designed hexode mixer valve. In Fig. 4 the unit on the right constitutes the oscillator and includes a tetrode. The heptode or pentagrid (five grids) performs the function of the mixer and the intermediate frequency signals are extracted from the anode circuit. Internal shield grids serve to prevent direct intercoupling between the electrode systems connected to the signal and oscillator circuits. The third method is one which utilizes a specially designed valve—triode hexode, or triode pentode in which the electrode systems of the oscillator and mixer are combined in the same bulb. Thus in Fig. 5 the triode hexode valve is shown with the right section of the valve diagram indicating the triode oscillator and the left-hand portion the hexode mixer valve.

In modern triode pentodes, electron coupling is obtained by an internal path between the oscillator grid and the pentode suppressor grid, the triode being connected as feed-back oscillator.

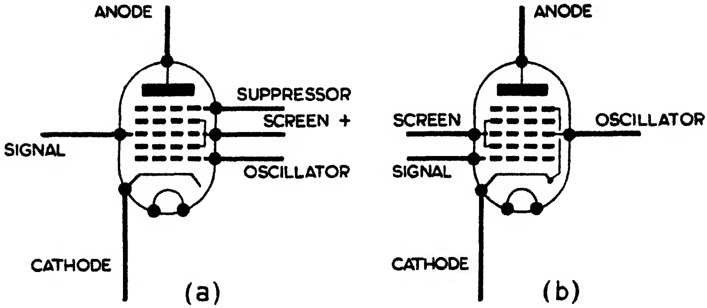


FIG. 6.—APPLICATIONS OF THE HEPTODE VALVE.
(*a*) As a frequency changer.
(*b*) As a mixer valve.

The screen grid of the pentode performs its normal function as a shield between the oscillator injection circuit and the signal circuit; similarly, the triode hexode is designed as a single valve frequency changer to work at frequencies higher than those at which the heptode and octode will operate at the best efficiency. Screen grids (Fig. 5) shield the oscillator injector grid from both hexode anode and signal grid and make the electron path through the valve one of high resistance. Interaction between oscillator and signal circuits is overcome by making the two electrode systems more or less independent and screened from each other. Injecting the heterodyne voltage into the grid nearer the output anode of the mixer valve reduces another type of interaction known as space charge coupling. Although only brief reference has been made here to valves since they are dealt with full in the section on valves, it should be noted that these multi-grid types can often be used with more than one method of connection (see Fig. 6).

Detailed Consideration

The principles so far set out seem all very simple and advantageous. They do not, however, represent the whole story and the full realization of their advantages introduces other problems and we shall now refer to some of the points which have to be attended to in order to secure a satisfactory supherhet receiver.

It has been explained how second channel interference is cut out by the use of a tuned aerial system and since the

intermediate frequency is constant, the difference in frequency between the aerial circuit and the oscillator must be the same over the whole scale so that the two tuning condensers must move together in step. This sounds easy enough by simply ganging or mechanically coupling them together, but it must be remembered that the two circuits do not tune over the same frequency range, and the ratio of the highest to the lowest frequency is not the same in the two cases. The oscillator condenser has to start its scale with a higher minimum and finish at the other end of the scale with a lower maximum then the aerial condenser. The higher minimum can be secured by connecting a fixed condenser in parallel with it. The lower maximum can be secured by the addition of a series connected fixed condenser.

Either of these devices will correct at one end of the scale, but the ganging of the two condensers will not be correct at intermediate points. Consequently a combination of the two has to be used. The small series connected capacities are known as tracking or padding condensers. Vernier or trimmer condensers of very small capacity enable any residual errors to be corrected and the two circuits to be aligned at one point of the scale so that they are correctly in tune at all other points. Another method is to use specially shaped condenser plates, since by this means, the capacity at different points of the scale can be made to follow any law. This method however, while it secures correct alignment of the two circuits on say the medium wave band, when the set is switched over to long wave reception, the two circuits are badly out of step again.

Radio-Frequency Amplification

The use of an amplification stage at signal frequencies is also employed to reduce second channel interference, but it also introduces problems of its own. It will have been noticed from the previously quoted examples that the frequency separation between the wanted signal and its second channel interference is twice the intermediate frequency. Consequently, it is easier to tune out and get rid of the second channel interference by making the intermediate frequency higher. On the other hand the use of a high intermediate frequency, of course, opposes the main advantage of the superhet which, as we have seen, is that the intermediate frequency is made lower than the signal frequency.

Consequently, a compromise between the opposing requirements has to be adopted and in most modern receivers the intermediate frequency is in the region of 450 kc/s.

Beat Interference

Another form of disturbance is known as beat interference which must not be confused with the term we used earlier in this article to explain how the intermediate frequency was produced. Beat frequency disturbance is due to an outside transmitter which has the same carrier frequency as the superhet oscillator. The cure for this again is a selective tuned aerial circuit. It is not usually very troublesome unless the offending transmitter is very near and/or the receiver has a poorly selective aerial or high-frequency amplification stages.

Harmonics

In the design of a superhet receiver, care has to be taken to avoid distortion in the second detector. Distortion at this point implies that component harmonics of the intermediate frequency are produced and if these feed back and get mixed with the signal frequencies, beats may be produced which will seriously upset the reception. Interference may also be produced if the oscillator generates impure oscillations which include harmonic components of the fundamental frequency. The harmonics may beat with any outside transmitters which could produce the right intermediate frequency and may thus get into the receiver as a spurious disturbance. For instance, suppose the oscillator frequency is 400 kc/s and the signal frequency 300 kc/s giving an intermediate frequency of 100 kc/s. If the oscillator has say harmonic frequencies of say 800, 1,200 or 1,600 kc/s these will beat with any transmitters having carrier frequencies respectively of 700 kc/s, 1,100 kc/s or 1,500 kc/s, since any of these will give rise to the required 100 kc/s intermediate frequency.

Such disturbances were common in early receivers in which a triode valve was used for the double purpose of detection and oscillation. In modern frequency changer valves, the functions of oscillator and mixer are arranged to avoid harmonic generation. A separate valve as an oscillator is preferable to one used as a mixer and oscillator if one of the specially designed valves for this purpose is not available.

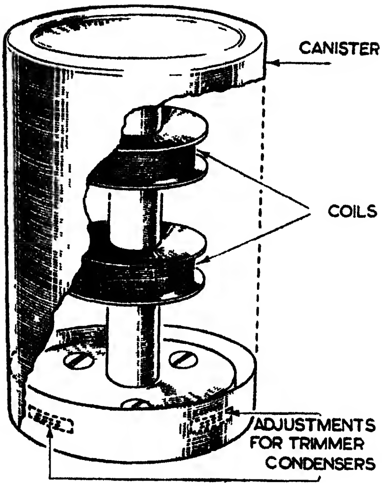


Fig. 7.—Typical Intermediate Frequency Transformer in Screening Canister.

Disturbance is also possible from transmitters actually broadcasting on, or near the intermediate frequency. Unless precautions are taken against it, these unwanted signals may get into the tuned intermediate frequency circuits. The intermediate frequency transformers are always efficiently screened to avoid direct pick up, and the aerial circuit may include a rejector circuit which offers high impedance to the reception of the unwanted signals, or an acceptor circuit which by-passes them to earth, the object in either case being to prevent them getting into the receiver. The short reference we have made to these possible sources of interference will be sufficient to show that the construction of a satisfactory receiver is not quite so easy as the first principles of its operation might lead us to suppose. All these problems have been satisfactorily solved, but it is easy to understand why in earlier days when many of them were only incompletely overcome, the superhet receiver acquired such a notoriety as a source of squeals and whistles. Nor are these the only factors which have to be considered. We will now refer to some further features which contribute towards the satisfactory operation of a receiver of this type.

Side Bands

Since the adjacent channel selectivity of the superhet receiver is vastly greater than that of any straight set, it might be assumed that as only one signal frequency has to be amplified, the intermediate frequency amplifier stages could be made as selective as possible so as to pass on to the following stages a very narrow band of wavelengths. This, however, is not so. Good quality speech and music demands that a whole band of

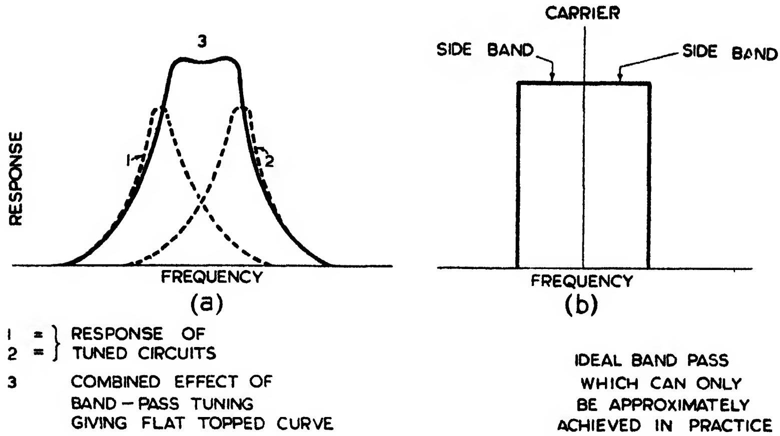


FIG. 8.—PRINCIPLE OF THE BAND-PASS FILTER.

frequencies, up to several kilocycles on either side of the high frequency carrier, shall be passed through the set unless the reproduction is to suffer badly in quality. These frequencies, or side bands as they are called, cover the complete range of audible frequencies. Thus, suppose the intermediate frequency is 450 kc/s, the amplifying stages must be capable of accepting and amplifying all frequencies in the band of 445-450 kc/s if the reproduction is to be good. Thus the intermediate frequency tuned circuits should not be made as selective as might at first be imagined, and if they are made so, some of the side bands will be cut and the quality of reproduction will be poor. To secure the acceptance of signals with the range referred to what are known as band pass tuned circuits or filters are employed.

Many forms of band pass filter can be devised. Each of these consists in principle of two tuned circuits, the tuning condensers being ganged together and the coils electrically coupled so that the two circuits are tuned to slightly different frequencies. Each alone would have the type of resonant circuit shown as (1) and (2) by the dotted lines in Fig. 8(*a*). The resultant effect is to produce an acceptance curve similar to that shown in (3) which is a very near approach to the ideal curve of Fig. 8(*b*). Another, and perhaps obvious method, is to cut off the side bands frequencies by making the circuits highly selective and then put back the missing frequencies by using a following

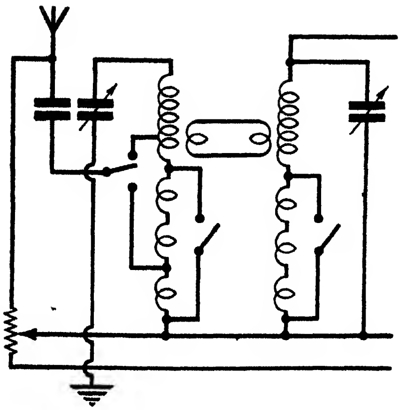


FIG 9—TYPICAL AERIAL BAND PASS FILTER.
Switching controls are used for changing wave range.

stage which amplifies the high or audible frequencies more than the lower ones. There are many cases, as for instance when a local station is being received, where the set is not required to be highly selective, and a variable selectivity control is the ideal arrangement. This is secured by varying the coupling between the coils of the intermediate transformer. When the coupling is reduced, the selectivity of the set is made less and the band of frequencies passed through made wider. The curve (3) of Fig. 8(*a*) is thus made wider without altering its shape. Similarly, increased coupling increases the selectivity, but makes the quality of reproduction worse.

Oscillator Drift

The oscillator frequency, in practice, is made higher than the signal frequency because a much smaller capacity is required to produce a given frequency change on a higher range than on a lower range, so that the tuning circuit can be made smaller. So far it has been assumed that for any given position of its tuning condenser, the oscillator frequency will always remain the same. Any variation in the oscillator frequency is serious, particularly on short waves, and any instability due to this cause will make it difficult to keep the intermediate frequency within the range of the intermediate frequency transformers. The main causes of oscillator drift are small temperature changes and variation of electrode voltages. Consequently, the power supply must have good voltage regulation and the condensers and coils must be such that their characteristics do not change as the set warms up after being switched on. Oscillator drift often occurs when the oscillator valve is getting near the end of its life and is apparent by fading of the reception, or the sudden switching over to another station without any apparent cause.

Noise

The degree of amplification which is possible in any set is limited by unavoidable disturbances, some of which take place inside the valves themselves, and which are all classified under general term "noise." Background noise has been greatly reduced by careful design in modern valves, but there is still one form of disturbance known as oscillator hiss which is heard when the sensitivity control is turned up to its limit. It is caused by small irregularities in the oscillator output which are passed on to, and amplified by the intermediate frequency stages and is in consequence reduced by limiting the degree of amplification. One method of doing this is to include an adjustable cathode bias resistance in the cathode lead of a variable mu valve so that its grid bias and, therefore, its amplification can be controlled.

Mistuning

The distortion which occurs in a superhet receiver when the desired station is not correctly tuned in, is well known to all listeners. The differences between the oscillator and signal frequency is then not exactly equal to the intermediate frequency for which the set is designed and although it is near enough to be accepted by the intermediate frequency transformers the side bands are unequally amplified. For this reason, it is desirable to include some form of tuning indicator to show the correct point of resonance. Automatic correcting devices are also included in some sets.

Short Wave Reception

All the precautions necessary in a straight set to avoid stray capacitive losses and feed back apply equally in any superhet receiver which includes the short wave ranges. As the signal frequency increases, the relative difference between oscillator and signal frequency becomes less and there is much greater tendency for one of them to force its resonant frequency on the other by the process known as "pulling." Consequently, much greater care has to be taken to prevent intercoupling by the selection of a suitable frequency changer valve, or by the use of a separate oscillator valve.

Conclusion

It has only been possible here to refer briefly to the main features of the superheterodyne receiver. The special devices for tuning which some proprietary sets include are described in the following pages, but no mention has been made of automatic volume control which involves certain problems peculiar to this type of receiver, and is dealt with in Chapters XI and XV. It will, however, have been understood that the heterodyne principle enables satisfactory reception to be carried out under most unfavourable conditions, e.g. portable sets and car radio.

TUNING INDICATORS

The high selectivity of modern radio receivers calls for some visual form of indicator to show when the station being received is accurately tuned in to the centre of the waveband accepted by the tuned circuits. The ear is not a sufficiently good indicator, and without some auxiliary device slight mistuning will cut off the lower frequencies and the reproduction will suffer in quality.

Milliammeters

The most obvious indicator is a milliammeter in the anode circuit of the detector valve. If a grid-leak detector is used the point of correct tuning will be that at which the anode current is a minimum. With an anode bend detector, maximum anode current will indicate correct tuning. The change in anode current of the detector valve to either a minimum or a maximum is thus a means of showing the point where the station being received is tuned in.

In the case of receivers which include automatic volume control, the milliammeter can alternatively be included in the anode of one of the A.V.C. controlled valves. When the station is off tune, the grid bias on these valves is low and the anode current is high. As the receiver is more closely tuned in, the increase in negative grid bias reduces the anode current so that the correct tuning point is indicated by minimum anode current.

A milliammeter, however, has certain disadvantages. It is expensive. It takes up a good deal of room, and, most important of all, it is not very sensitive to weak signals where the reading will be at one end of the scale and the maximum or minimum point not easily recognized.

Neon Discharge Tubes

Better alternatives are small neon discharge tubes, or the so-called magic eye indicators. The latter are used almost exclusively in present-day receivers. A typical example of the former type is the tuneon indicator consisting of a glass tube about 100 mm. long and about 13 mm. diameter, in which there are three electrodes.

The two electrodes between which the discharge passes are connected through a resistance between the cathode and the high voltage end of the anode transformer of one of the intermediate frequency valves. The third electrode facilitates the striking of the discharge. As the required station becomes tuned in, the voltage across the valve rises and the length of the discharge column increases. The indicator thus shows a pink line of light which has a maximum length when tuning is correct.

The Magic Eye Indicator

The magic eye indicator which has now replaced all other tuning indicators consists of a double electrode system comprising a miniature cathode ray tube and a triode in the same bulb. The electrode systems are mounted axially, the cathode ray system being uppermost. The common cathode is mounted along the axis of the bulb and is surrounded at its upper end by a concave annular electrode, the inner surface of which is coated with a fluorescent material to act as an illuminated screen, and is called the target.

A control grid connected to the triode anode serves to alter the distribution of electrons which flow from the cathode to illuminate the target. If this control grid is made negative, some of these electrons which flow out radially from the cathode will be repelled and a shadow in the form of a V sector will appear on the target. The higher this negative voltage, the wider the shadow.

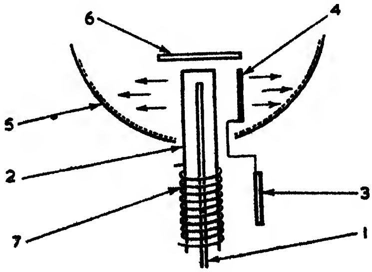


FIG. 10.—DIAGRAMMATIC REPRESENTATION OF THE ELECTRODE SYSTEM.
Electrode references as shown in Fig. 11.

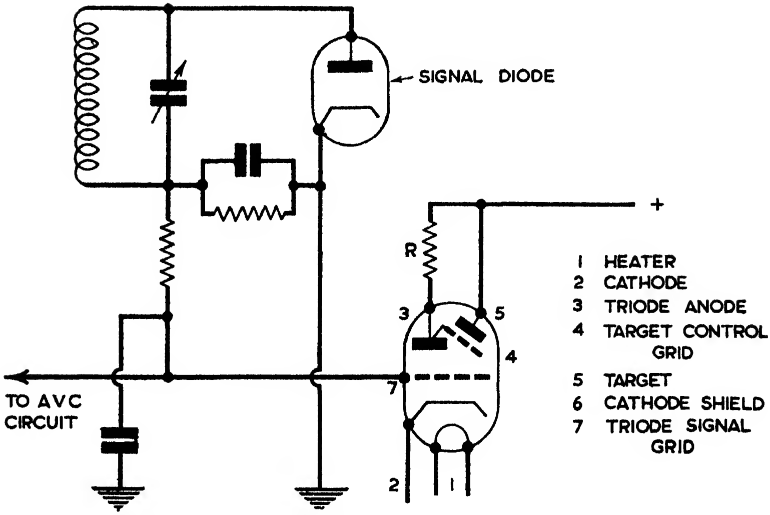


FIG 11 —METHOD OF CONNECTING MAGIC EYE INDICATOR

In order to make the device sufficiently sensitive to small voltage changes, a triode amplifier is included in the bulb to amplify the signals from the A.V.C. circuit. Fig. 10 shows a diagrammatic representation of the electrode system and Fig. 11 a typical method of connecting up in a receiver the same electrodes being numbered to correspond.

As the required station becomes tuned in, the A.V.C. voltage increases and the triode grid potential becomes more negative and the anode current through R decreases. Thus the control grid 3 becomes less negative with respect to the target, so that the shadow angle is reduced and becomes a minimum when the station is correctly tuned in. An excessive negative voltage on the signal grid 7 causes the two edges of the fluorescence on the target to overlap and give a patch of extreme brightness (Fig. 12). This condition overloads the valve and must be avoided by the use of suitable circuit component valves.

AUTOMATIC TUNING DEVICES

To relieve the listener of the trouble of accurate tuning, auto-tuning devices for selection of a limited number of stations have been introduced into some receivers. Three distinct methods of automatic tuning have been employed.

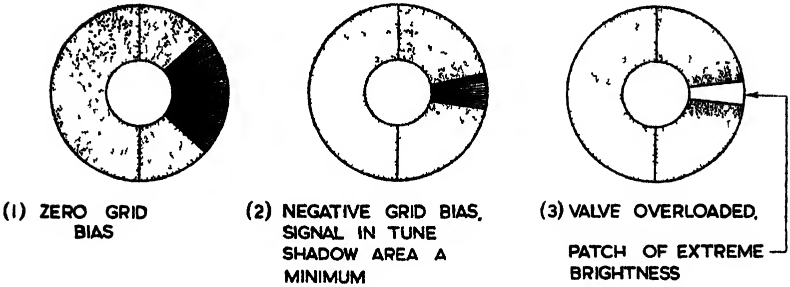


FIG 12—OPERATION OF THE MAGIC EYE INDICATOR

Push-Button Systems

Push-button operation involving only mechanical action is the most popular method. Several different forms of such systems exist and they must all, if successful, be free from backlash or slackness in the moving parts, which would produce small changes in the condenser movement after a period of use.

One system includes a series of spring-loaded plungers terminating on the instrument panel in push-buttons, each labelled with a particular station and carrying a bell crank fixed in a position inclined to the axis of the plunger. When the button is pushed, this crank comes into contact in turn with each of two diametrically-mounted bosses on the end plate of the condenser spindle, so that the condenser spindle is turned to a fixed position and remains there until one of the other plungers with a differently inclined crank is pressed to bring in another station.

Another device involves a rack-and-pinion movement in which the plunger attached to the push-button opens out into a toothed fork, the upper and lower portions being parallel with each other. Each side of the fork engages with a toothed wheel which has on its periphery a turned-over lug. These lugs cause similar projections on two metal discs, which are left free, to rotate and these, in turn, press against a lug on the remaining disc, which is clamped to the main drive of the condenser spindle. The coupling between the lever pushed and the condenser spindle is such that the levers have the same amount of travel irrespective of the amount the tuning condenser is rotated.

In another system, each push-lever serves to advance the movable member of a tubular or spiral meshed condenser by lateral movement. Each push-lever has a different length of travel and when depressed is locked in position by the

engagement of a pawl and released to return under the action of a spring only when one of the other levers is depressed.

Switching Controls

This is merely an extension of the principle by which any set is switched over from the medium to the long wave band. In principle, to switch in one of several stations, one inductance with several pre-selected condensers, or one condenser with one of several different inductances, can be employed to secure resonance at the required tuning point. Owing to the possibility of change in capacitance of a condenser after some use, variable inductances of the iron dust core type are employed, and the principle of varying them is known as permeability tuning. All the tuning circuits of the receiver have their corresponding switching circuits ganged together.

Motor-driven Devices

Owing to the power consumption involved, the use of a small motor to rotate the tuning condensers to the right position, is confined to mains-operated sets. The motor drives the condenser through reduction gearing when one of the push-buttons is depressed. There are several systems which differ principally in the means adopted for stopping the motor at the correct point. One method involves the use of a sector plate geared to the condenser spindle, and this engages one of several fixed contacts corresponding in position to the preset stations. When the condenser reaches the correct position an insulating piece on the sector plate interrupts the motor circuit.

In such motor drives the correct tuning point is only approximately attained and a further circuit known as automatic frequency control (A.F.C.) is then brought in to correct the residual error. This is carried out by a double diode valve, known as a discriminator. Its function is to compare the frequency to which the set has been left tuned with the designed intermediate frequency of the receiver. The output circuit of the valve produces a resultant signal, the polarity of which depends on whether the automatic tuning device has left the circuit tuned slightly above, or slightly below, the correct point.

This signal is applied to the oscillator circuit and slightly adjusts the oscillator frequency in the direction which corrects the residual tuning error.

CHAPTER XV

AUTOMATIC VOLUME CONTROL

THE strength of the signals received by an aerial may vary over a wide range due to unavoidable changes and attenuation which takes place in the transmission medium. These are due partly to changes in reflection of the Heaviside layer *q.v.*, variations in the phase between the direct and reflected waves and to some unknown factors, all of which may cause the loudness of the reproduction, if not in some way counteracted, to vary widely without any adjustment of the tuning or sensitivity controls. These variations in signal strength are known as fading, and if the circuit is a simple one, the reproduction may be at full volume at one instant and will then gradually fade away, becoming practically inaudible over a period of a few seconds. This was an effect prevalent in early receivers.

There is, of course, no control over the causes of fading, but it is possible to include in the receiver an auxiliary circuit which will, at any rate, partly counteract the effects of fading and enable the loudspeaker to reproduce at practically a constant level of sound. The circuit which is included to secure this result is known as the automatic volume control or A.V.C.

Varying the Receiver Amplification

The way in which the sound level is evened up will be, perhaps, almost obvious. If the set can be controlled automatically, without adjustment by the listener so that its amplification is increased when the reception is weak and reduced when the reception is strong, the effects of fading will be at any rate partly corrected. If the sensitivity is adjusted initially at the point where a comfortable level of sound is secured, the reproduction will remain at the same degree of loudness irrespective of the strength of the signals received by the aerial. Since the signals received may vary over a range of, say, 100,000 to 1, it is fairly

clear that complete correction is hardly possible, but with modern receivers changes in the level of audibility due to fading are scarcely noticeable.

The Variable-mu Valve

It has already been explained in the valve section, that the variable-mu type of valve employed in the radio-frequency amplification stage has an anode current/grid voltage curve with a low slope at low values of grid voltage. It is, therefore, possible to employ a fairly wide range of grid voltage to control the amplification of this valve without seriously affecting its performance in other directions, so that a form of pre-detector volume control is made possible by adjustment of the grid bias. Automatic volume control enables the signal intensity to provide a variable grid bias for the predetector valve, or valves, and thus vary the amplification of the set.

The A.V.C. reduces the gain of the receiver when the received signals are strong by increasing the negative grid bias of the first valves in the receiver and *vice versa*.

Circuit Details

A simple circuit illustrating the mode of operation of A.V.C. is shown in Fig. 1. The control is carried out by the detector valve. In the case of a diode detector, which is most usual, the operation of rectification and A.V.C. may be performed by the same diode or, in the case of a double diode, each diode may perform one function. Reference should be made to the section on diode detection in Chapter XIII, where the close connection with the circuit here referred to will be noticed.

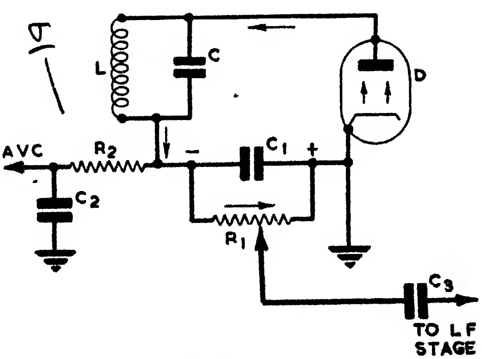


Fig. 1.—Simple Form of Automatic Volume Control.

In Fig. 1, LC is the tuned secondary of the last intermediate frequency transformer if the set ~~is a superhet~~erodyne receiver, or the secondary of the radio frequency transformer if a straight set. On each positive half cycle of the signal, the anode

of valve D is made positive and then current flows through it, electrons passing from cathode to anode round the circuit, as shown by the small arrows.

The oscillatory currents carrying the signal modulation are thus rectified, as explained in the chapter on signal detection. Though always flowing round the circuit of Fig. 1 in the same direction, the current is made up of two components, a steady and a variable component. The variable component again consists of two frequencies, the audio or signal frequency with which the listener is ultimately concerned and the intermediate carrier frequency.

Current Components in the Diode

The steady component and the audio-frequency signals pass through resistance R1, which is called the diode load resistance, but the intermediate frequencies pass through condenser C1 which is of low impedance to high frequencies but offers a high resistance to audio frequencies and presents a complete barrier to steady current. The intermediate frequencies are thus by-passed from the load resistance R1 and do not concern us further. The signal voltages are taken from the tapping point of R1 and fed through C3 to the first low-frequency valve.

The steady current produces a voltage drop across R1 of the polarity shown in Fig. 1. This voltage is proportional to the amplitude of the carrier, or the strength of the incoming signals, and is conducted back through the filter R2, C2 (whose function will be referred to later) as a variable negative bias to the grids of the preceding valve or valves. Thus, when the incoming signals increase, the D.C. voltage across R1 rises and the negative grid bias of the R.F. and I.F. valves is increased, so that the stronger aerial signals do not produce anything like such an increase in output from the set as they would if A.V.C. were not employed. Similarly, when the received signals decrease, the A.V.C. operates in the reverse direction.

Incidentally, it should be noticed that A.V.C., though primarily intended to counteract fading, also forms a convenient means of preventing overloading by strong signals.

Mode of Applying the A.V.C. Voltage

The A.V.C. voltage is usually fed back to the R.F. valve grid in a straight receiver, or to the I.F. and frequency changer valve as well, in a superhet. The magnitude of the signals handled

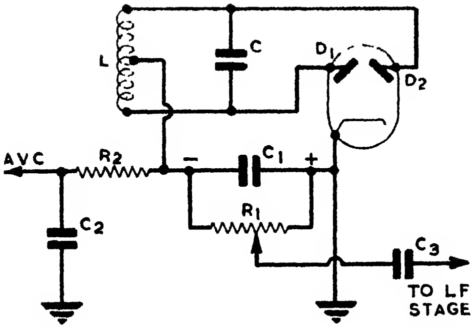


FIG. 2.—DOUBLE DIODE DETECTOR VALVE GIVING FULL-WAVE RECTIFICATION AND A V C

by these valves differs greatly so that the magnitude of the grid bias required by each valve is quite different. The R.F. variable-mu valve will require a grid voltage change for full control which if applied to the I.F. valve would badly overbias the latter, causing it to rectify and produce serious distortion.

When the A.V.C. is applied to more than one valve, therefore, separate tappings are taken off the diode load resistance. Thus, in Fig. 1, the full A.V.C. voltage is fed back by the connection shown to the first valve and lower voltages, suitable for the frequency changer valve and the first I.F. valve, could be taken from intermediate tappings determined by the particular valves in use. Fig. 2 shows the same circuit as Fig. 1 but with a double diode valve giving full-wave rectification. In both cases rectification and A.V.C. are furnished by the same circuit.

Bias Connection to the R.F. Valve

The usual method of applying the A.V.C. bias is shown in Fig. 3 and is sometimes known as series feed. The tuned grid circuit is here isolated by condenser C1 from earth for direct voltages. Condenser C1 is necessary, otherwise the A.V.C. voltage would be connected to earth and would not control the valve grid. The usual cathode resistor R, with its smoothing condenser C, provides an adjustable steady grid bias which enables the initial state of the valve to be pre-set before the A.V.C. comes into operation.

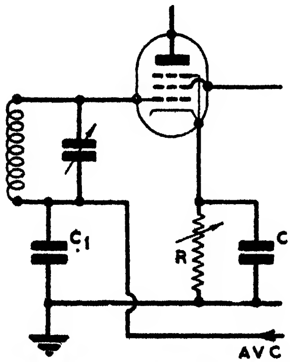


FIG. 3.—USUAL METHOD OF APPLYING A.V.C. VOLTAGE TO PRE-DETECTOR VALVE STAGE.

Though condenser C1 isolates the A.V.C. from earth, it has a very low impedance to H.F. voltages so that for oscillatory currents the tuned circuit

is still virtually earthed. The existence of C1 slightly alters the effective tuning capacitance of the grid circuit but, if kept low, its effect is small.

An alternative and less generally used method consists in applying the A.V.C. voltage direct to the valve grid and isolating the grid from the tuning circuit by a small fixed condenser. This condenser virtually performs the same function as C1 in Fig. 3.

Fig. 4 shows a variation of the previous circuits. Here, the diode D1 functions as the detector. A part of the signal voltage is transferred through condenser C4 to diode D2 which performs the A.V.C., resistance R2 being the A.V.C. load, and the voltage across it controls the pre-detector valves.

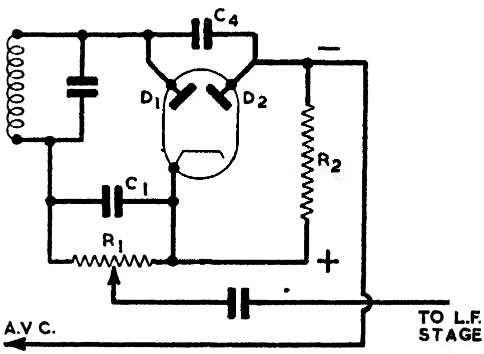


Fig. 4.—Detection and A.V.C. Voltage Provided by Separate Diodes.

The Filter Circuit

In Fig. 1, reference has been made to the filter comprising resistance R2 and condenser C2 in the A.V.C. lead. If these components were omitted, the audio-frequency signals would pass along the A.V.C. lead and would vary the gain of the receiver at audio frequencies. They would, in fact, smooth out the modulation of the incoming carrier wave.

The function of this decoupling filter is, therefore, to prevent the audio, or signal voltages from coming back through the A.V.C. lead. Since resistance R2 is in series with condenser C2, this condenser cannot charge up instantaneously or, in fact, alter its voltage quickly. The A.V.C. voltage is not, therefore, able to vary the audio-frequency signals individually, but operates fast enough to compensate for signal fading and alteration in the average signal strength.

Delayed A.V.C.

When the signals received from a distant station are very weak, it is naturally desirable to use the maximum amplification of which the set is capable, in order to get a satisfactory output. Under such conditions, it would be obviously undesirable for

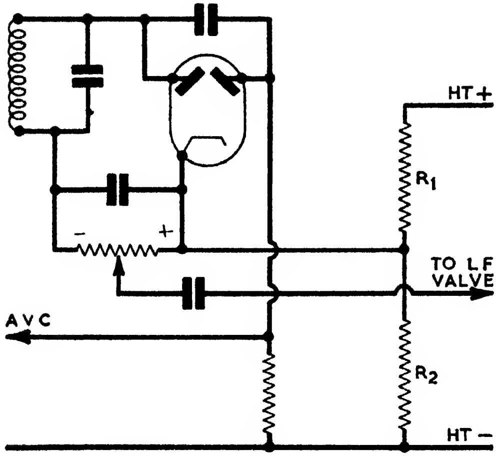


FIG 5 —DELAYED A V C.

The circuit illustrated is the same as for Fig. 4, but the cathode is given a small positive bias to delay the operation of the A V C

the amplification to be reduced by the action of the A.V.C. coming into operation. One method of cutting out the A.V.C. under such conditions is to alter the circuit so that it only begins to function when the signals exceed a certain minimum strength.

This can be done by giving the A.V.C. diode a negative bias voltage which keeps the anode normally at about 2 or 3 volts negative to the cathode or, what amounts to the same thing, by making the cathode positive to the same extent. Thus before the A.V.C. can function, the signal voltage must exceed the negative anode bias of the diode, since no current can pass through the valve until the anode is positive to the cathode.

Fig. 5 shows the same circuit as Fig. 4, but with the cathode of the double diode valve given a small positive bias provided by the voltage drop across R2 so as to delay the operation of the A.V.C. In this circuit the function of the signal diode D1 is not affected by this modification.

Another method of biasing the diode is to connect the diode cathode to a point on the grid bias resistor of the following low-frequency amplifier valve so that, again, the diode cathode is given a fixed positive voltage.

Modifications

A number of elaborations of these basic principles are included in modern receivers. In some cases, the two diodes of a double diode valve are connected together to produce a lower valve impedance and both then function as a combined signal detector and A.V.C. valve.

Increased selectivity and a higher input voltage to the detector is also secured by feeding it from the primary instead of the secondary of the previous intermediate frequency transformer. Since the diode detector does not amplify, the gain is naturally smaller than with a triode detector. It is common practice to use a double diode triode valve in the detector stage, so that the signal voltage can be amplified in the triode section before passing on to the low-frequency amplifier valve. There are several ways in which such a valve can be connected in the receiver, but its most usual mode of operation will be clear from the basic principles outlined.

Amplified A.V.C.

Where the simplest form of A.V.C. does not give sufficiently good control of the output, a further modification may be adopted. This consists in amplifying the A.V.C. voltage before applying it to the pre-detector valves. A simplified diagram illustrating the way in which a circuit of this kind functions is shown in Fig. 6. In principle, the double diode section of the valve here functions in the same way as the circuit of Fig. 4, but the triode grid is fed from the diode load resistor and the valve cathode is biased positively by resistor R1, giving delayed A.V.C. for diode D2.

If now a strong signal arrives, the negative voltage applied to the triode grid increases due to the increased direct voltage drop across R. This results in a reduction in current through the valve and resistor R1, the cathode resistor bias is thus made less, diode D2 becomes more positive and an A.V.C. voltage is produced across resistor R2. The amplifying property of the triode is thus used to secure increased A.V.C. voltage.

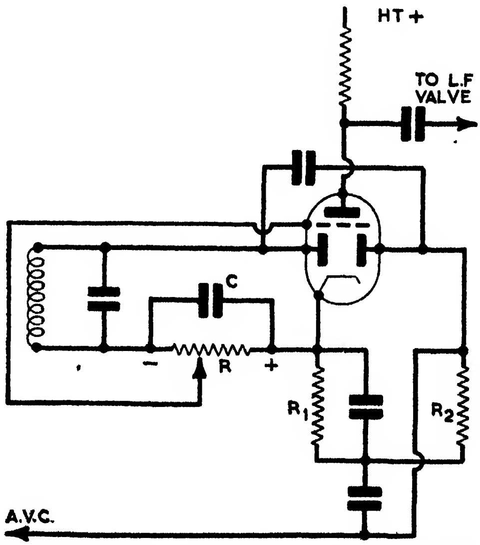


FIG. 6.—SIMPLIFIED CIRCUIT TO ILLUSTRATE THE PRINCIPLE OF AMPLIFIED A.V.C.

Noise Suppression

One disadvantage of the simplest form of A.V.C. is that the sensitivity of the receiver is greatest when no signals are being received so that, between the station tuning points, there will be excessive background noise. Numerous forms of circuit have been used to overcome this. Some of them are quite complicated, and space here permits of only a brief mention of the principle involved in one of them.

This arrangement employs the same principle as that already mentioned as being used to secure delayed A.V.C. but, in this case, it is the signal diode and not the A.V.C. diode which is negatively biased. This means that the detector valve is normally cut off and does not function at all until a signal of pre-set minimum intensity comes in to overcome the diode bias and allow it to function by passing current through it. The signal diode, in this case, acts as a signal operated switch which cuts out the valve when very weak signals, or no signals at all, are being received. A.V.C. circuits including noise suppression devices are sometimes referred to as quiet automatic volume control, or Q.A.V.C.

CHAPTER XVI

LOW-FREQUENCY AMPLIFICATION

Low-frequency amplifiers provide the necessary means of increasing the intensity of the audible signals which have been separated from the radio-frequency carrier wave and which are too weak to give adequate volume of sound when passed directly into the reproducer. The need for such amplification arises, not only in broadcast radio receivers, but also with low frequency signals from microphones or gramophone pick-ups. In a broadcast receiver some amplification does, in the case of grid detection, take place in the detector, but in spite of this, the power available is nearly always low enough to demand at least one low-frequency stage. Similarly, in the case of microphone or pick-up signals, a low-frequency amplification stage in addition to the output valve is generally provided to furnish adequate reserve of power.

Principles of Low-Frequency Amplification

It will have been understood from the section on valves, that the valve is a voltage operated device, small changes in voltage on the signal grid producing relatively large changes in anode current. These changes in anode current, can, by suitable coupling circuits, which include resistances, condensers or transformers, be passed on as voltage variations to a second low-frequency valve if the amplification is still insufficient. An essential condition is that in all such processes, the character of the voltage or current changes shall not be materially altered, otherwise the sound reproduced will suffer in quality.

Both the nature of the signals and the function of the amplifier stages differ from the corresponding high-frequency stages. In the high-frequency stages, the signals are of radio

frequency, modulated by the low-frequency components, and the amplifier valves are concerned purely with voltage amplification. Before reaching the low-frequency stages, the audio-frequency signals are separated in the detector stage from the radio-frequency carrier which is rejected and prevented from entering the low-frequency stages of the receiver. It is one of the essentials of satisfactory receiver design that the separation and rejection of the high-frequency carrier shall be complete. Distortion of reproduction, or instability, may result if the high-frequency carrier is only incompletely separated and a portion of it gets into the low-frequency section of the receiver. In the high frequency stages of a receiver, we are concerned with voltage amplification, or increasing the strength of the modulated high-frequency waves to the point where they are adequate in intensity to operate the detector valve satisfactorily.

The first stage of the low-frequency section of the receiver is also concerned with voltage amplification of signals of audible frequency, but the last stage is concerned solely with current or power amplification, since the sound reproducer—the loud speaker or headphones—depends for its operation on the power it receives from the last valve of the set and which it converts into sound vibrations, conveyed finally through air to the ear. As with high-frequency valves, the stages may be coupled or connected together by means of condenser-resistance or transformer paths, though, as will be evident from further consideration, the values of the components and, in some instances, the function they perform are quite different.

Anode Current Components

Before considering these cases separately in more detail, it should be remembered that the anode current through the valve of a low-frequency amplifier when receiving signals, in the simplest case, consists of two components: (1) A direct current component from the power supply, of constant magnitude, which exists whether signals are being received or not and sometimes called the standing current; (2) An alternating current of varying amplitude and frequency which fluctuates in step with the incoming signals. There are some low-frequency amplifier circuits in which the first of these two

components is partly or completely eliminated during the periods when no signals are being received. These will be considered later.

Resistance-coupled Stages

At present, we will consider the arrangement shown in Fig. 1. To make the explanation as simple as possible, we will take a battery operated triode as an example, each valve being supplied with a separate grid bias battery. In mains operated sets, the valves would be grid biased by resistors in the cathode leads. Let us consider the circuit of Fig. 1 when no signals are being received. Anode current from the valve V_1 passes through the resistance R_1. The magnitude of this current will depend on the voltage of the power supply, the value of the resistance R_1 and the resistance of the path between the anode and cathode inside the valve.

At the moment we need not concern ourselves with the value of the resistance of the last part of the circuit. It will be sufficient to assume that the current has some value, say I. If the voltage of the supply is E_p, there will be a loss in voltage across resistance R_1 and the valve anode will receive a lower voltage than the supply :—

$$\text{Valve anode voltage} = E_p - IR_1 \quad . \quad . \quad . \quad . \quad (1)$$

We must remember that I is a steady direct current and since condensers present a barrier to such currents, the existence of condenser C_1 need not yet concern us.

Now consider the effect of an alternating signal voltage on the grid of the valve. Suppose an instantaneous change of voltage equal to e occurs on the valve grid, and suppose that the valve has an amplification factor of μ. This is really equivalent to saying that the grid voltage change e produces a voltage of μe in the anode-cathode path of the valve. It does not mean that the step up in voltage

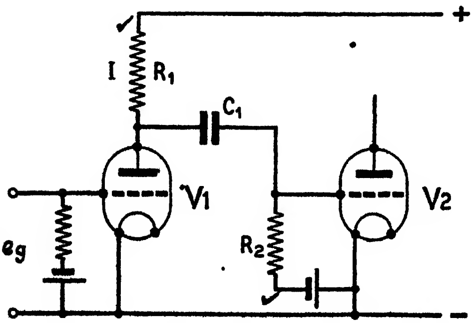


FIG. 1.—SIMPLEST FORM OF RESISTANCE COUPLED L.F. VALVE STAGE.

due to the amplification of the valve is μe, because, as we shall see, only part of this voltage change is passed on to the next valve.

Amplification secured by the Valve

We will at first neglect the existence of condenser C_1 and resistance R_2. If, as indicated in Fig. 1, the valve anode resistor has a value of R_1 and the A.C. resistance of the valve is R, the proportion of the voltage μe which appears across each depends on the relative values of R and R_1. The voltage which is passed on to the next valve is the change which appears across R_1; that across the valve V_1 is not utilized. Since these voltages are proportional to the values of the resistances, the amplified signal voltage is :—

$$\frac{\mu e R_1}{R_1 + R} = \frac{\mu e}{1 + R/R_1} \quad . \quad . \quad . \quad (2)$$

It will be noted from the second expression, that the value of amplified signal increases as the denominator is made smaller, i.e., as R_1 is increased relatively to R. The A.C. resistance of the valve is, of course, fixed under given conditions so that the user has no control over it, but it will be noted by reference to any valve maker's catalogue that all low-frequency and power output valves have fairly low impedances.

It might be assumed from the previous statements, that since the amplification increases with the value of the anode resistor R_1, we could increase the amplification as much as we wished, by merely increasing R_1. If, however, we look again at expression (ii) we see that the denominator can never be less than 1, which value is attained when R/R_1 is zero, i.e., when R_1 is infinitely large. Under such conditions, the voltage amplification would be equal to the amplification factor of the valve. In practice, of course, this condition can never be secured and the voltage step up is always something less than the amplification factor of the valve.

In fact, the value of the anode resistance which can be usefully employed is limited by another factor. As its value is increased, the voltage drop across it, due to the steady direct current component is also increased, which means that the voltage on the anode of the valve is reduced. It must be remembered when looking up the characteristic of any particular valve, that the anode voltage means the voltage between the anode and cathode

and not the supply voltage. The valve anode voltage is always less than the supply voltage by that lost in the anode resistor.

Now, as the anode voltage of a valve is reduced, its amplification factor is also reduced and the valve does not amplify so well. Thus, what is gained in amplification, by increasing the anode resistance above a certain value, is offset by the fact that the valve does not work so well at its lower anode voltage. If, therefore, full advantage is to be taken of increasing the anode resistance, the supply voltage must also be increased and it is not always possible to do this.

In practice, with a constant supply voltage, it will be found that the effective amplification rises rapidly as the anode resistance is made greater than the valve impedance. This occurs up to the point where it is about twice as great, after which the increase becomes less rapid until it has become about three times as great. There is, therefore, little advantage in making it any larger. Thus, with a valve of say, 15,000 ohms impedance, the optimum value of anode resistance is about 45,000 ohms. The actual value, of course, is not critical and the resistor must be dimensioned so as to carry the rated anode current of the valve and be capable of dissipating I^2R_1 watts without overheating.

Similar conditions apply more or less where the supply voltage is increased to maintain the valve anode voltage constant, but with the difference that the degree of amplification secured is, in all cases, considerably greater which serves to indicate the advantage of sufficiently high voltage for the anode circuit.

RESISTANCE CAPACITY COUPLING

The signal voltage amplified by the valve must be passed on with a minimum of loss to the following circuit. If this is a further valve stage and resistance-capacity coupling is being used, the condenser C_1 provides the necessary signal path, since it permits alternating potential to pass through it, but entirely blocks the way to direct current. Such a condenser is necessary also, because without it, the full supply voltage would reach the grid of valve V2 and make it highly positive, causing the cathode emission to be excessive, which would destroy the valve.

The reactance which the condenser C_1 offers to the passage of the signal voltage is lower the higher the frequency $\left(= \frac{1}{\omega C_1}\right)$, and consequently it must be large enough not to offer too much obstruction to the lowest frequency signals which have to be handled. In addition, we have to consider the effect of the negative charge on the grid resulting from electrons out of the cathode stream which hit it (*c.f.* grid detection). If grid current flows in the valve, the grid will collect these electrons and assume a negative potential. Means must, therefore, be taken, to remove this accumulated charge from the grid, or else the valve anode current will be reduced, or may even be cut off entirely, so that the valve cannot function as an amplifier. A leakage path of suitable value must, therefore, be connected between the grid and the filaments of valve V2 (Fig. 1).

Grid Leak Resistance

This resistance R_2 allows the charge on the coupling condenser to leak away and not affect the signal voltage changes which are passed on from the preceding valve.

Condenser C_1 and grid leak R_2 are in series with one another and although the lower end of resistance R_2 differs in potential from the upper end of the anode resistor R_1 by the full supply voltage, these two points are, as far as the alternating signals are concerned, at the same A.C. potential so that condenser C_1 and resistance R_2 are really in parallel with the anode resistor R_1 and act as a shunt path to it.

Thus, it will be clear that if serious loss in signal strength is to be avoided, as it must be, the impedance of this shunt-path must be high compared with the value of the anode resistance R_1. There is also another shunt path in parallel with the grid leak R_2, i.e., the internal path between grid and filament in the valve. We will consider this later.

From these remarks, it will be fairly clear that if the value of R_2 is too low it will weaken, or attenuate the signals by reducing the voltage changes across the anode resistance R_1. On the other hand, if it is too high in value, the negative charge on the valve grid, previously referred to, will not be able to leak away fast enough and the grid will be unable to follow the signal voltage changes.

Another way of putting this, is to say that the time constant of the grid circuit will be too high if R_2 is too large and, being biased or choked by the accumulated charge, will be unable to follow the signal input voltages faithfully.

With regard to the path between the grid and cathode inside the valve, the grid leak must not be comparable in value with the resistance of this path, otherwise it will exert a short-circuiting effect on the valve. Normally R_2 will have a value of something between 0·25 MΩ and 2·0 MΩ, the lower values being used with the larger valves. The more massive the electrode system, the greater the necessity of limiting the effect of positive ion grid current by keeping the value of the grid leak relatively low.

Value of the Condenser

The condenser C_1 usually has a value somewhere between 0·001 mfd. and 0·1 mfd.

This condenser with the grid leak R_2, forms a potentiometer and the portion of the voltage across R_2 is applied to the grid of valve 2. In order that the proportion of the voltage across R_2 shall be as large as possible, that loss across condenser C_1 must be kept small, i.e., the reactance C_1 must be kept to a minimum at the lowest audible frequency since its reactance is greatest at low frequencies. For example, suppose this condenser has a capacity of 0·03 mfd., then at the lowest frequency, say 50 c.p.s. to be amplified its reactance will be approximately 105,000 ohms. With a grid leak of 1 MΩ there will, therefore, be only about

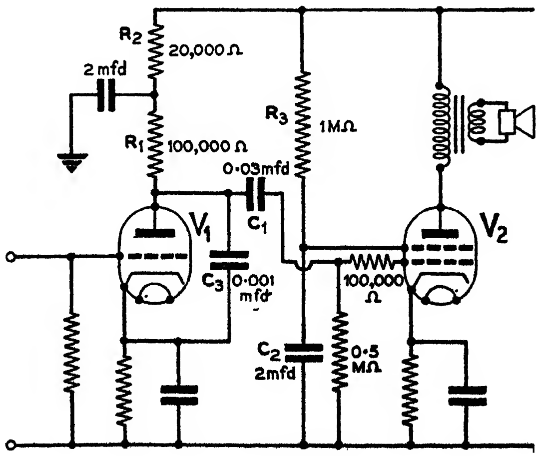


FIG. 2.—TYPICAL STRAIGHTFORWARD LOW-FREQUENCY R.C. AMPLIFIER.

The values of the cathode bias resistors depend on the valves used. R_1, R_3 are decoupling resistances and C_3 is included to by-pass any H.F. currents not removed by the detector stage.

10% loss in signal strength at 50 cycles and at all other higher frequencies the loss will be considerably less. These, therefore, represent suitable component values which fulfil reasonably well the conditions previously mentioned. Fig. 2 shows a typical low-frequency amplifier stage with suitable component values for coupling a medium impedance valve to a low-power triode.

TRANSFORMER COUPLING

An alternative method of transferring the low-frequency signals from one stage to the next in a low-frequency amplifier is by means of an iron cored transformer (Fig. 3). One advantage of the transformer type of coupling is that by winding the secondary with a larger number of turns than the primary, a step up in voltage can be secured and the signal voltage changes on the grid of the following valve still further increased It might at first be thought that by making the ratio of the secondary turns to the primary turns very large, a very great step up could be secured, but this is not so because other effects are present.

In a rather similar way to the case of the resistance coupling previously considered, in order that the voltage input to the primary winding shall be high, the inductance of the primary winding should be as large and the impedance of the valve as low as conveniently possible. The case is not quite the same as that of the resistance type of coupling, because the transformer primary is inductive and this introduces a phase change. Nevertheless, although this is a complication which we will not consider further here, the general conclusions we shall arrive at are substantially true. Then again, there are small capacities between the windings and although these are not of much concern at very low frequencies, they become more pronounced at the higher frequencies. Electrostatic capacity exists between the two windings, between different turns of the same windings, and between each winding and the core. All these stray capacities are indicated in Fig. 4. They can be reduced, of course, by suitable disposition or sub-division of the windings, though this is a matter which concerns inter-valve transformer design.

There are also other factors, such as eddy current losses, which are controlled by laminating the iron cores so as to present

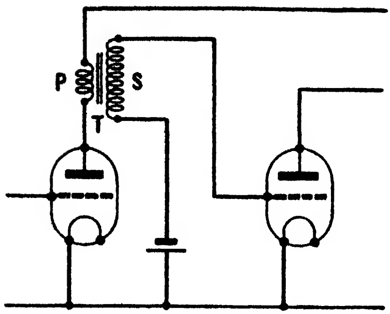


FIG. 3.—SIMPLEST FORM OF TRANSFORMER COUPLING.

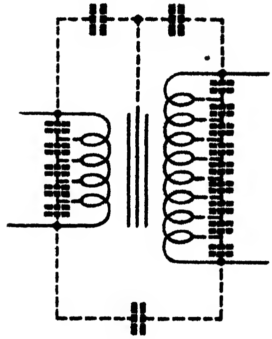


FIG. 4.—STRAY CAPACITIES IN THE WINDINGS OF A TRANSFORMER.

as difficult a path as possible to such circulating currents; and leakage reactance which represents a loss due to the fact that some of the magnetic flux passing through the primary does not link the secondary winding. The effect of both these losses is approximately the same as a shunt resistance across the primary winding.

As we have seen that the transformer primary should have a high inductance which means many turns of wire, a large step up in voltage would involve such a large number of turns on the secondary that the electrostatic capacity of the winding would be appreciable. In consequence, some of the higher audible frequencies would be shunted through these capacity paths and would not reach the following circuit. Consequently, the useful step-up obtainable from the transformer is limited. If it is made too large, the quality of reproduction gets worse. A step-up ratio of 1 : 4 is about as large as is generally employed. In some power transformers the step-up is less.

Resonance

The stray capacities of the transformer windings may, however, have another interesting and useful effect. With the leakage reactance, they constitute a resonant circuit at some particular frequency and as this frequency usually lies near the upper end of the audible range, their effect is to improve the frequency response in the region where it would otherwise tend to fall off. To a limited extent this effect is sometimes utilized in improving the performance of the circuit.

Secondary Load

In Fig. 3 the grid-cathode circuit of valve 2 is connected across the secondary winding of the coupling transformer and constitutes its load. Now it is a common feature of any transformer that increase of load on the output winding reduces the output voltage. Consequently, if the signals passing through the transformer are not to be appreciably reduced from this cause, the input impedance of the following valve must be high. This condition is secured by operating valve 2 with a sufficiently high negative bias so that the voltage fluctuations never cause the grid to become positive and produce appreciable grid current which, in addition to being a load on the transformer secondary, will also produce distortion in the reproduction.

Frequency Response

An ideal receiver will, of course, reproduce a given strength of input signal at a fixed output level whatever the frequency. Since the circuit components have characteristics which vary at different frequencies, some care has to be taken to ensure that this condition can be approximately attained. A good inter-valve transformer can be expected to give the same degree of voltage step-up to all signals over the greater part of the audible range. At very low frequencies the step-up will be reduced because the primary inductance is reduced. At high audible frequencies stray capacity effects will predominate and cause a similar reduction in voltage given.

Parallel Feed

The passage of the steady direct current component through the transformer primary serves no purpose except to give an

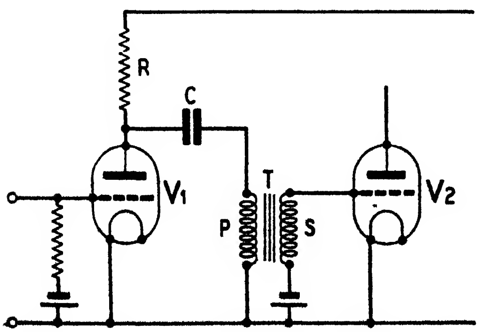


FIG. 5.—PARALLEL FEED TRANSFORMER COUPLING.

Condenser C bars the passage of D.C. from supply, but passes the signal alternations.

initial magnetization to the core. This is a disadvantage in the case of some of the high permeability nickel-iron cores which are now used and which enable the size of the transformer to be greatly reduced. The initial magnetization reduces the primary inductance, and we have seen that a high primary inductance is a desirable feature. Consequently, one of several alternative methods of connection which are rather like a mixture of resistance and transformer coupling and which are known as parallel-fed connections are employed for the purpose of eliminating the direct current through the primary and passing through it only the alternating currents, due to the incoming signals.

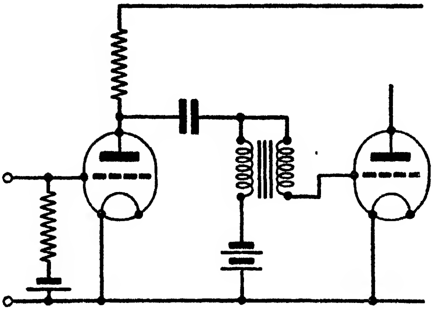


FIG. 6.—PARALLEL FEED WITH WINDINGS CONNECTED AS AN AUTO-TRANSFORMER.

Circuit for Parallel Feed

The most usual form of parallel feed connection is that shown in Fig. 5, where condenser C bars the passage of direct current from the supply but passes the signal alternations through the transformer primary winding P. In order that such an arrangement may work satisfactorily, the circuit through the condenser C and the transformer primary winding P must present an easier path to the signals than the anode resistance R, otherwise the greater part of the signal will pass through R and not through C. The anode resistor, therefore, must be high compared with the impedance of the condenser path, but not high enough to reduce seriously the voltage on the anode of the valve. The value of the condenser C is usually selected so that it forms a resonant circuit with the transformer primary at some point in the lower end of the audible range where the amplification normally tends to fall off.

Fig. 6 shows another method of connecting the windings in the form of an auto-transformer connection. Of the several alternative methods, the simplest case where the two windings are separated gives the highest voltage step up.

The Output Stage

The last valve in the receiver is concerned with increasing the power in the signal currents which have been amplified by the preceding valves and of transferring that power to the sound reproducer in the most efficient manner. The power handled by the output valve may vary from a fraction of a watt, in the case of a small domestic receiver, to many watts in the large valves used in public address equipment. The current changes in the anode circuit of the output valve are transferred to the sound reproducer through a transformer. The alternating currents in the speech coils of the reproducer must be as large as possible without impairing their character as magnified replicas of the incoming signals. To attain these conditions represents practically the whole problem of the design of an efficient output stage.

Though the transference of power to the reproducer is the chief object of the output valve, this valve does also provide some amplification, so that, other things being equal, the valve impedance should be low and its mutual conductance as high as other factors permit.

We have now to consider (1) the conditions which must be fulfilled to produce the maximum power in the signals in the output valve, (2) the most efficient method of transferring that power from the valve to the loud speaker.

CONDITIONS FOR GOOD REPRODUCTION

For any given valve there is a certain value of the anode load which gives the best performance and which in consequence is known as the optimum load. It does not represent the load which gives the maximum power output because a greater output of power can be obtained by using a load impedance differing from the optimum value, but only at the expense of poorer quality of reproduction. It is, therefore, a matter of securing the highest power consistent with good quality.

Falling off in quality of the reproduction, due to overloading the valve, is caused mainly by the introduction of harmonics of the fundamental frequencies, chiefly the second harmonic. The ear can tolerate a certain amount of harmonic distortion, and it has been established that 5 per cent. of second harmonic can be present without perceptibly affecting the quality of the sound.

In power output valves, the anode current fluctuations are large so that the anode voltage may vary over a wide range. Consequently, the operating point does not remain on the same anode voltage/anode current curve. The essential conditions for good reproduction are (1) that the operating point shall not pass off the straight portion of the characteristic curves, (2) that the grid voltage shall never become positive. How these conditions can best be fulfilled is perhaps most easily explained by using an example referring to one particular valve. Take, for instance, the R.C.A. output triode type 2A3. The published anode voltage/anode current curves are shown in Fig. 7. The anode voltage is rated at 250 and the anode current at 60 milliamps. These figures (point B) represent typical conditions when no signals are being received.

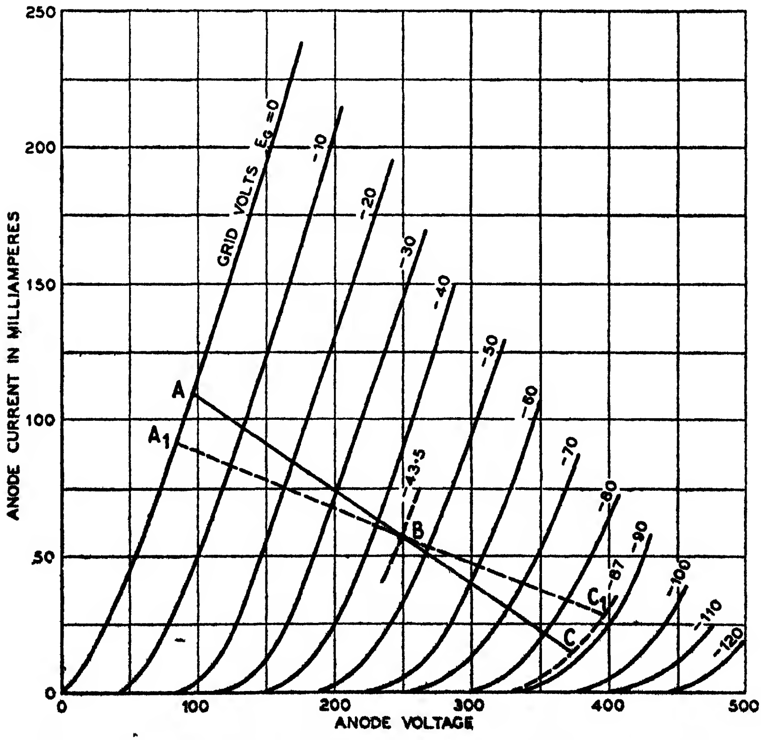


FIG. 7.—LOAD LINES OF A TYPICAL POWER OUTPUT VALVE, TYPE 2A3. Average plate characteristics.

(Radio Corporation of America.)

Anode Dissipation

Since the voltage across the valve is 250 volts when the steady current passing is 60 milliamps, the power dissipated in the valve is $\frac{250 \times 60}{1000} = 15$ watts. We say, therefore, that this is a 15-watt valve. This does not mean that the valve will deliver 15 watts of sound energy, and although almost all makers' valves are liberally rated to the extent that they can be loaded in excess of the published figures, the actual power converted into sound when the loudspeaker is giving good reproduction, and known as undistorted output, will be very much less. In fact, it may at first seem that the anode dissipation has no connection with the sound output since it represents power being wasted even when no signals are being received, and it may, therefore, well be asked why it is necessary at all. However, it is related to the sound output and it represents the average power level of the valve. The sound energy, as we have seen, is due to the A.C. or fluctuating component of the anode current. The anode dissipation, which is a measure of the energy the valve can handle and is proportional to the heat developed in it, represents the energy level about which the A.C. current changes can fluctuate. Since, obviously, the amplitude of the energy fluctuation cannot become less than zero, the A.C. energy can only be large if the valve dissipation is high.

The heat due to the anode dissipation has to be got rid of by conduction and radiation, otherwise the electrode system will get too hot, gas will be released from the bulb and the valve will be damaged. Each valve has a maker's rating for maximum anode dissipation which represents the maximum anode voltage and current the valve will safely stand, and these figures should not be exceeded.

Optimum Load

We shall now see how the fluctuations in anode voltage and current, the undistorted output and the anode load are related to each other. Consider the valve previously mentioned operating at the point represented by B. Under these conditions with no signal voltage and a grid bias voltage of $-43 \cdot 5$ volts, the anode voltage is 250 and the anode current 60 millamps. Suppose now the grid voltage fluctuates symmetrically about this point, rising

to zero in one direction and increasing in the negative direction to $-$ 87 volts. These conditions can be represented by the points A and C respectively, A, B and C being points in one straight line called a load line. The slope of this line will depend on the value of load in the anode circuit. At the point A, the anode voltage will have dropped to about 100 volts due to the higher anode current which is about 120 milliamps. At the point C the anode current has dropped to about 12 milliamps. and the anode voltage increased to about 360 volts.

The total fluctuation in voltage between the points A and C is thus about 260 volts, and the total fluctuation in current about 108 milliamps. These changes correspond to an anode load of $\frac{260 \times 1000}{108}$ ohms = 2,500 approx. This is the maker's published figure for the optimum load, so that the line A B C represents the best conditions of working for this valve. We could, of course, have started off with an assumption of the value of the anode load and calculated from it the voltage and current variations.

If we did this, say, assuming a larger value of anode load, we should get points corresponding to A_1 and C_1, where A_1 BC_1 is the equivalent load line. In fact the higher the anode load, the less the slope of the load line. It should be again emphasized that the optimum load is that which gives the best all-round performance and not the one which produces the greatest power output. The optimum load value is not, of course, very critical, and no great change in performance is noticed until it departs appreciably from its optimum value.

Power Output

The sound output is due to the alternating current component in the output valve. Assuming in the example quoted, all the energy is converted into sound, the voltage fluctuation from peak to peak was 260 volts corresponding to an average R.M.S. value of $\frac{260.}{2\sqrt{2}}$ The corresponding average R.M.S. value of the current is $\frac{95,}{2\sqrt{2}}$ so that the power output is $\frac{260 \times 95}{8 \times 1000} = 3{\cdot}12$ watts. The maker's published rating is 3·5 watts.

Factors Governing the Quality of Reproduction

By making the anode voltage and current fluctuate over wider limits, the power output of the reproducer can be increased at the expense of the quality of the sound, which becomes progressively worse as the load is made greatly different from the optimum value or conditions (1) and (2), previously referred to, are not fulfilled. This is due to the unsymmetrical swing of the grid voltage and the fact that harmonics of the fundamental frequencies, not present in the preceding stage, are introduced and appear in the output circuit so that the sound waves are not a true copy of the current changes in the previous portion of the receiver.

It has been mentioned that the second harmonics are the chief contributors to this loss in quality. Without going into detailed calculations, it can be said that the extent of second harmonic content present in the output is measured by the amount of asymmetry in the grid voltage swing, *i.e.*, by the difference of the steady value of the anode current and the average of the peak values (Fig. 7). This means that when the current and voltage swings are symmetrical on either side of the mean values, the distortion is negligible and the departure from this symmetry is a measure of the distortion in the reproduced sound. Other harmonics beside the second also contribute to the distortion, but the second is usually the chief offender. In pentode valves other factors enter into the considerations and the calculations become more involved so that only an outline of the simplest case is referred to here.

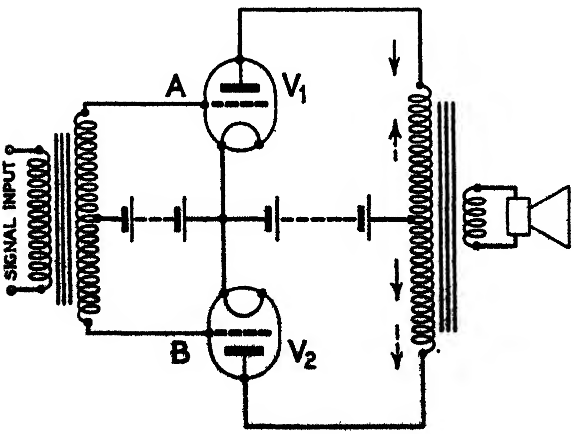


FIG. 8.
PRINCIPLE OF CLASS A, PUSH-PULL AMPLIFICATION.

The full arrows indicate the direction of current change due to signals. Dotted arrows indicate the direction of D.C. components.

In practice, of course, the sound output will vary over a wide range, being greatest for the loud passages and changing with the depth of modulation, so that the valve should be considerably larger than is required to fulfil the conditions of average reproduction and so that it can handle the loud passages, where the power required is much greater, without any deterioration in quality. Very often this condition is not fulfilled. It is quite common to hear a set which gives tolerably good performance at medium loudness " blast " badly when loud passages come along.

PUSH-PULL AMPLIFICATION

Assuming all other conditions required for satisfactory amplification are satisfied, the volume of sound which can be made available depends on the size of the output valve. In other words, the larger the output valve the more powerful the reproduction possible. Theoretically a large output valve should give about the same output as two smaller ones of half the wattage dissipation operated in parallel. Parallel operation of valves, however, has some undesirable features. Not only must the valves be provided with separate grid bias to balance up any inequalities in characteristics so that they share the load equally, but during their subsequent life, the characteristics may change sufficiently to upset this balance so that one takes more than its share, becomes overloaded and gives a short life. A much better method, and one which has certain merits of its own, is to connect the valves in the manner shown in Fig. 8. This " back-to-back " connection is known as Class A push-pull and has long been in use as an efficient method of securing the maximum power output from the receiver. Fig. 8 shows the arrangement in its simplest form. It permits of several modifications which will be dealt with later.

The signals from the penultimate stage are fed to the push-pull connected valves through a transformer, the secondary of which is centre tapped, the ends being connected to the valve grids and the centre point fed from a battery so that both grids are given negative bias. During signal reception the operating point does not pass over the bottom bend of the grid volts/anode current curve and the grids never become positive.

At any instant during reception, when the grid voltage of V_1

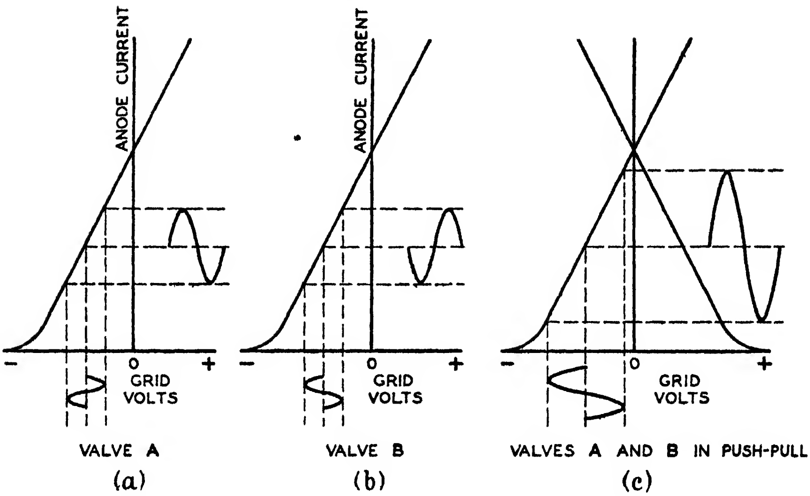


Fig. 9.—Effect of the Grid Swings of Two Vaves in Push-Pull on the Resultant Anode Current.

is becoming less negative, that of V_2 is becoming more negative, and *vice versa.* The grids are always in opposite phase so that while the anode current in V_1 is increasing that in V_2 is decreasing. A centre-tapped transformer has its primary winding connected in the common anode circuit so that the changes in current in the two valves can be made to produce additive effects in the secondary winding to which the loudspeaker is connected. This result is secured by the fact that although the current changes at any instant in the two valves are in opposite directions, these currents pass through the two halves of the transformer primary also in opposite directions so that their effects assist one another.

The two valves do not, as might at first appear, take turns in amplifying, but both are performing this function all the time. Their operation is analogous to that of two men sawing a tree trunk with a saw having a handle at each end. At one moment one man is pushing and the other pulling; then they reverse and the first man pulls while the second man pushes, and so on, both contributing his share to the work all the time.

This effect can also be shown by reference to the grid volts/anode current curves of the valves. Fig. 9 (a) shows the anode current fluctuation for a given fluctuation of grid volts for valve A when considered alone. Fig. 9 (b) shows the corresponding anode

current change for valve B. If now the curve of Fig. 9 (b) is reversed by rotating it about the vertical axis, representing a 180° phase change and is then superposed on Fig. 9 (a), it will be seen that the grid swings in the two valves operating simultaneously assist one another in their effects on the resultant anode current. This is shown in Fig. 9 (c).

Advantages of Push-pull

Push-pull amplification has some other notable advantages, which are perhaps best summarized thus :—

1. The direct current component of the anode currents in the two valves, shown by the dotted arrows in Fig. 8, are in opposite directions through the primary of the anode transformer so that their magnetic effects cancel each other and the impedance of the primary winding is thereby increased—a desirable feature as we have already seen.
2. The signal input voltage is divided between the two halves of the grid transformer so that the input circuit can handle double the grid voltage swing of a single valve operating as a Class A amplifier.
3. Second (and other even) harmonics cancel out in the centre-tapped transformer. This means that for a given grid voltage swing the circuit gives less distortion than a single valve. This and other factors enables the total output to be increased rather more than twice the output of a single valve. Hence its wide use in high quality receivers and public address equipment.

It should be noted that the effective amplification is only half that secured from a single valve since the signal voltage is divided between the two valves. This is not of great ~~importance since~~ the main function of the output stage is not high amplification but the efficient transfer of power to the reproducer.

In a single valve amplifier stage, it is essential that the working point shall remain on the straight portion of the characteristic curve if distortion in the reproduction is to be avoided. Further consideration of Fig. 9 will show that with push-pull connection, the grid voltage can swing so as to move over a part of the bottom bend of the curve and produce an unsymmetrical fluctuation in the anode current, without producing very much

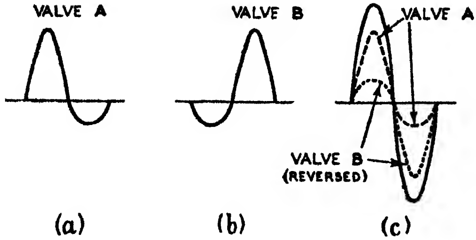


FIG 10—RESULTANT CURRENT CHANGE WITH UNSYMMETRICAL ANODE CURRENTS IN EACH VALVE
(a) A C component of anode current in valve A
(b) A C component of anode current in valve B
(c) Resultant symmetrical current change in push-pull connected valves

distortion, because such changes are equal and opposite in the two valves, and so, to a large extent, almost cancel each other as indicated in Fig. 10.

Class B Amplification

The above principle is used in Class B amplification, where the valves are operated at the bottom bend of the curve. This has the great advantage that the D.C. component or standing current in the valve is greatly reduced, which means less drain on the battery supply when no signals are being received; a great economy for battery sets where the power supply is restricted. Under such conditions of working, the positive portions of the signal impulses in, say, the first valve, will cause the anode current to rise and fluctuate in step with the signals, but the negative impulses will have little effect since the anode current is already biased practically to zero. The second valve, however, by reason of its phase opposition, will handle those portions of signal which the first cannot, so that the whole of the incoming signals will be amplified either by one valve or the other. As distinct from Class A push-pull, the valves amplify in turn, not simultaneously.

Going back to our analogy of the two men sawing the tree, if both men decide only to push in turn and not to pull at all, we have what is equivalent to the action of valves in Class B amplification. We could almost call the arrangement a push-push instead of a push-pull. Now in a Class B amplifier, since anode current only passes during signal reception, the anode dissipation of the valve is that due to the A.C. or signal power, so that electrically the valve is working much more efficiently. In consequence, smaller and less costly valves can be used for a given output. While the anode current fluctuates between a maximum and

zero, the anode voltage varies over a wide range, so that the supply must have a good voltage regulation. For this reason, Class B amplification is practically limited to battery receivers. In addition, the wide variation of anode current precludes the use of automatic grid bias resistors.

The full theoretical advantages of Class B amplification are only possible if the valves have the same characteristics, particularly in neighbourhood of the bottom bend of the curve which is not covered by Class A amplification. The nearest practical method of securing the same performance is by matching or selection and, since this is never perfect, a form of distortion peculiar to Class B and producing even harmonics in the output, resulting in high-pitched quality and more accentuation in weak than in strong signals is sometimes produced. Tone correction circuits in the output or the grid circuit are often included to overcome it. Some manufacturers produce special valves with a dual electrode system and a common cathode in the same bulb, to achieve closer identity of performance.

Positive Grid Drive

In order to secure high efficiency and fully utilize the wide voltage swing possible, the grid potential in the case of triodes has to be allowed to become positive during part of the cycle. Positive grid potentials we have seen are normally most undesirable since they cause grid current to flow and damp the signal input, due to the load imposed on the transformer secondary, and thus produce distorted reproduction. In Class B amplifiers this is overcome by the use of a step-down transformer with a low resistance secondary, which will provide the current required in the grid circuit rather than act as a voltage coupling device. The primary side is connected in the anode circuit of an additional or driver valve whose function it is to provide power for the following grid circuit. There is thus the disadvantage of an extra valve.

Resistances are frequently connected across the transformer secondary and included to prevent spurious oscillations. A stopper resistance is often included in the grid of the driver valve. In the case of pentode output valves, it is possible to secure sufficient grid voltage swing without it becoming positive. Quiescent push-pull is the name given to pentode output valves operating in this way.

Class AB Amplification

In order to take advantage of some of the good points of both Class A and Class B amplification, push-pull connected valves are sometimes operated with grids biased to some intermediate point, less negative than Class B and more negative than Class A, so that anode current passes during part of the negative signal cycle. This method of connection, which is a mixture of Class A and Class B, is known as Class AB. Class AB amplifiers are further divided into Class AB_1 and Class AB_2. In Class AB_1, the peak signal voltage is never greater than the negative grid bias, so that the grid is never driven positive. In Class AB_2, the grids are driven positive and draw grid current. The power required in the grid circuit must then be provided by the driver stage. Inverse feed back (*q.v.*) is often applied to push-pull, Class A and Class AB, amplifiers (see Fig. 11), but owing to the resistance introduced into the grid circuit, it is not generally applied to circuits drawing grid power.

CATHODE FOLLOWER CIRCUITS

It is often required to connect the output of a valve to a low impedance load. An analagous case occurs where a loudspeaker of low impedance has to be coupled to an output valve, the optimum load of which is large compared with the impedance of the speech coil. In order to secure an efficient transfer of

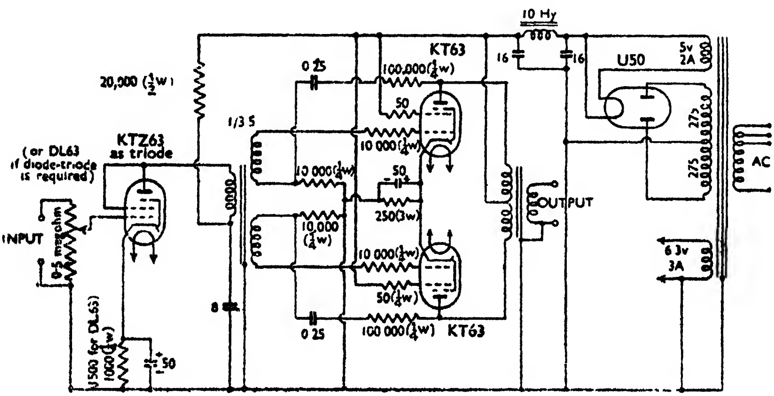


FIG. 11.—TWO VALVES IN CLASS AB_1 PUSH-PULL AMPLIFIER CIRCUIT. With negative feedback.

power from one circuit to the other, the coupling must be made through a step-down transformer of the correct ratio so that the load circuit is matched to the load impedance of the valve.

An alternative means of coupling a high-impedance input circuit to a low-impedance load can be provided by a valve operated in a cathode follower circuit (Fig. 12).

Advantages

This is a convenient arrangement where no suitable transformer can be secured. It also has the merit of being able to handle a very wide band of frequencies from megacycles down to zero frequency (D.C.) under which conditions a transformer cannot be used.

It is also free from other characteristics inseparable from a transformer, such as variation in the inductances of the windings at different frequencies, distortion, resonance, etc.

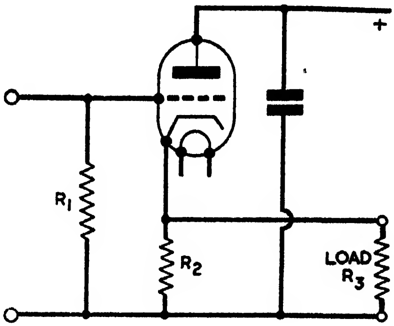


FIG. 12.—CATHODE FOLLOWER CIRCUITS.

Cathode follower circuit operating as an impedance transformer for a wide band of signal frequencies.

Applications

The need for such a device is thus obvious where a very wide band of signal frequencies has to be handled, as in the case of the picture signals of a television receiver, where uniform amplification over the whole of the frequency band is necessary.

With the usual forms of aperiodic valve amplification stage, the input impedance of each stage is connected across the load of the previous stage, and as this impedance varies with the signal frequency, it becomes less as the frequency is increased.

This effect is naturally not present where tuned circuits are used, but then, of course, tuned circuits cannot be used with wide band amplifiers.

Circuit Details

The cathode follower circuit (Fig. 12) involves a cathode resistor R_2 in the cathode lead. This resistance must not be shunted by a condenser, as in the case where it provides

automatic grid bias. In the most usual case, the load resistance R_3 matches the cathode resistor R_2.

The cathode follower is merely a coupling stage. It is actually a special form of negative feed-back (*q.v.*) where the feed-back is 100 per cent., and it therefore provides no amplification. The output voltage is approximately equal to the input voltage.

Since the signal voltage across R_1 is very nearly the same as the voltage across R_2 and these two voltages are opposite in phase, the alternating potential between the grid and cathode of the valve is very small and the cathode voltage thus " follows " the grid voltage.

Besides being useful as a buffer stage, the cathode follower has all the advantages associated with negative feed-back circuits, namely, absence of noise and distortion and freedom from disturbance due to relatively large changes in supply voltage, or valve characteristics.

VOLUME COMPRESSION AND EXPANSION

Methods of controlling the mean level of the sound output from a receiver by manual adjustment, and automatic devices for correcting the effects of fading have already been dealt with. Another and more difficult case is that of dealing with audio signals which vary over a very wide range of intensity. For instance, suppose a microphone pick-up is transmitting a speech and the speaker suddenly goes up very close to the microphone. Normally, this will result in a great boost of sound from the loudspeaker, the reproduction will not only become uncomfortably loud, but will probably badly distort as well.

The requirement is, therefore, to even up the sound level without the introduction of distortion. Devices included in receiver circuits for this purpose are known as volume contractors or compressors.

Volume Compression

Most circuits for volume compression work on the following principle: the grid bias of one valve of the receiver is made to increase automatically so as to reduce amplification when the sound level rises unduly. Without going into circuit details,

the general principle can be understood. A typical compressor circuit is that in which a part of the A.C. output is fed to a diode rectifier, the output of which is smoothed and the variable direct voltage obtained is employed as a variable grid control voltage for one of the valves of the set.

It is thus a special kind of automatic gain control like A.V.C., but with the difference that while A.V.C. functions by the use of the rectified carrier, the compression circuit uses the modulation or audio-frequency component.

The signal channels through the amplifier may be divided into two paths, one channel being subject to volume compression and feeding the output circuit; the other being uncompressed and operating the diode control circuit.

The diode filter circuit must have a "time constant" of the right order. Otherwise, if the time constant is too long, compression will be over accentuated and will persist after the need for it has passed. If too small, the action will be fast enough to cut out normal reception.

Volume Expansion

If the polarity of the diode output is reversed, the circuit will work in the opposite direction, so that volume compression becomes volume expansion. An illustrative example of both occurs in the recording and reproduction of sound on discs. In such recording there is always an unavoidable background noise, and the weakest recorded sound must be strong compared with this background. In consequence, say an orchestra is being recorded, if the weakest sounds have to be above a certain minimum, the loud passage will be so powerful that the recording stylus will have a large movement and will tend to cut through one groove on the disc to the next.

Now this trouble can be overcome, in the first place, by the use of a compression circuit, of the kind previously mentioned, in the recording circuit, and, secondly, to include a volume expansion circuit in the reproducer. Thus, the modulation is compressed in order to get it satisfactorily recorded on the disc and then expanded again in reproduction to secure all the fidelity of the original sound.

Combinations of expansion and compression circuits are also used in long-distance radio transmission for the elimination of noise and static disturbances.

Pre-emphasis

A rather similar case occurs in the transmission of speech where a particular form of disturbance partly due to noise and partly due to distortion is liable to occur. It is due to the fact that the intelligibility of speech depends much more on the high-pitch notes than on the low ones. On the other hand, the high-pitch notes are of low amplitude compared with the low ones. Consequently, noise tends to make speech difficult to understand, because it blots out the low amplitude high-pitch notes.

The effect can be, to a great extent, corrected by passing the speech through an amplifier which accentuates the high-pitch frequencies and they are then said to be " pre-emphasised," to make them strong compared with " noise " disturbances.

After transmission, the reverse process is applied to take out the shrill tone and restore the reproduction to the quality of normal speech.

CHAPTER XVII

LOUDSPEAKERS, MICROPHONES, AND PICK-UPS

IN the loudspeaker, the current changes in the output valve are converted into air pressure changes or audible sound. In all cases this is achieved by a suspended movable member, which is caused to vibrate through the attraction and repulsion of a magnetic field. The ideal loudspeaker would, of course, convert all the alternating current energy of the output valve into sound ; it would reproduce notes of all frequencies to the same extent ; it would not accentuate some more than others, and it would not introduce any tones which are not in the original signals. The whole problem of loudspeaker design and installation is to ensure that these ideal conditions are approached as nearly as possible. Since all loudspeakers have movable parts, these will have a natural period of vibration of their own, depending on their mass, the stiffness of their supports, etc. As a very small power will produce a large vibration at the resonant frequency, notes of this frequency will be unduly accentuated, therefore care has to be taken to design the speaker so that its natural period of vibration does not appear in the audible scale where it will be troublesome.

The earliest loudspeakers were large editions of the telephone headphones. The swan-necked horn speaker, which bears the obvious marks of antiquity, was common in early receivers. Sets were limited in output due to low efficiency in the valves then used and the main object was to get sufficiently intense sound in the direction of the listener. Following the established practice of gramophone construction, a horn of some sort was the obvious solution. The need for directional projection of sound in domestic receivers, to secure a comfortable level of intensity, has long ceased to exist and no such receivers now use horn speakers. They are still employed in public address equipment, but great attention has been paid to the

shape of the horn in such cases and they differ widely from the early types.

Loudspeakers can be classified into three main types :—

(*a*) Electromagnetic or moving iron types, in which the diaphragm or reed connected to a sound distributor is driven by the varying intensity of an electromagnet. These are now only found in old sets.

(*b*) Moving coil types in which the speech currents are passed through a light coil of wire, suspended in the field of a magnet.

(*c*) Special types, such as crystal elements, condenser speakers and a number of others which are less well known and mainly only of historic interest.

The early diaphragm type of speaker gave way, at first, to the reed type of movement and the horn was replaced by the cone as a sound distributor. A number of different forms of reed movement were used in turn as the demand for more and better quality reproduction increased. A popular successor to

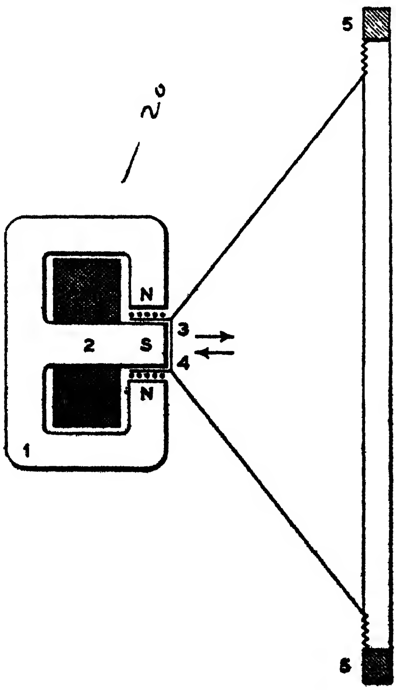
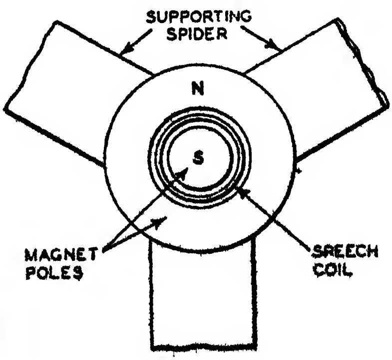


FIG 1 (*Left*)—ELEMENTS OF MOVING COIL LOUDSPEAKER (Sizes of Magnetic System exaggerated for clearness)

FIG 2. (*Below*)—END VIEW OF MAGNETIC SYSTEM OF MOVING COIL LOUDSPEAKER. (Diagrammatic only).



the reed form of speaker prior to the general adoption of the moving coil unit was the inductor type of speaker. This involved two separate magnetic systems excited by the speech currents and the moving parts consisted of two iron armatures rigidly fixed to each other and to the driving stem, but movable relative to the magnet system through a spring suspension. Excitation of the speech coils caused changes in magnetic fields so that the two armatures attached to the cone moved in the same direction at any given instant.

In all these types, the speech currents were passed through the fixed portion of the system. In modern speakers this condition is reversed and the moving part of the system carries the speech currents. It was soon found that moving iron speakers could not produce a sufficient volume of sound in low notes. The reason for this was that to produce a low note of reasonable intensity requires a relatively large movement, and the extent of movement was limited by the rigidity of the reed.

Moving Coil Speakers

All modern receivers include moving coil speakers, the essential parts of which are shown in the diagram of Fig. 1. A massive magnet (1), which may be electrically energized or alternatively a permanent magnet, has a centre pole (2), and in the narrow pole gap is suspended a light former carrying the speech coil (3). The latter is held in position by a centring device and attached to a diaphragm and cone (4). The cone is held round its edges by a flexible suspension (5) supported by a baffle to which the chassis is bolted. The clearance between the speech coil and the field magnet is small but sufficient to permit movement of the coil in the direction of the axis of the cone. The centring device enables the stationary position of the coil to be adjusted so that it does not foul the pole pieces. The magnetic field due to speech currents in the moving coil is at right-angles to that of the surrounding magnet and the attraction and repulsion between the two fields tends to move the diaphragm in the direction of the arrows shown in Fig. 1 against the restraining force of the flexible suspension. By suitable design, the extent of the coil movement can be made proportional to the strength of the current through the speech coil. The vibrations are distributed to the surrounding air by the attached cone.

The Magnetic System.—For mains operated receivers, ample electric power is available, so that it is possible to energize the speaker field coil as an electromagnet. In A.C. mains sets a common method is to use the field winding as a smoothing choke in the output circuit of the rectifier valve (*q.v.*). To prevent ripple in the unsmoothed current through the field coil producing hum in the speaker, an additional winding, known as a hum-bucking coil, is included in series with the speech coil. This is wound in opposition to the speech coil so that currents of hum frequency induced in these two coils produce equal and opposite effects and cancel each other. In battery sets it is obviously impracticable to spend power for field excitation so that a permanent magnet has to be used. A permanent magnet speaker can, of course, be used with a mains set if required.

The large number of turns of wire needed to produce the required degree of magnetization with a wound field results in a winding of appreciable resistance and when used as a rectifier output smoothing choke this means a considerable drop in the D.C. voltage available for the receiver. For A.C. mains sets this does not introduce any difficulty, because the secondary of the mains transformer can always be wound to deliver a correspondingly higher voltage to counteract the loss of voltage across the speaker field. In A.C./D.C. sets, where the D.C voltage available is limited to something less than the supply voltage, the voltage drop across the speaker field cannot always be tolerated and a permanent magnet speaker may be necessary. Alternatively, such a high resistance coil can be connected across the rectifier output terminals, as shown in Fig. 3, where it imposes an additional current loading on the rectifier valve, but does not account for any appreciable loss in voltage to the set.

The Speech Coil.—To obtain a speech coil with anything like the optimum impedance of the output valve would require a coil

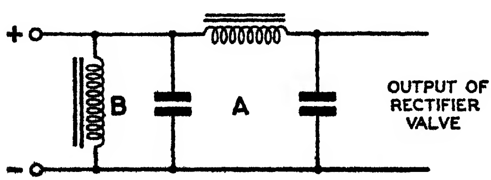


Fig. 3.—Parallel Connection of Loudspeaker Field.

A—Rectifier smoothing network.

B—Parallel connected loudspeaker field.

with a large number of turns and to accommodate this in the small space available very fine wire would be needed. Not only would such a coil be difficult to wind, but it would also involve trouble with insulation and would be of appreciable mass. To secure lightness and robust construction, it is obviously preferable to have a speech coil of low resistance and although high resistance coils have been made, it is established practice to use a low resistance coil and couple this to the output valve through a step-down transformer. The transformer is usually attached to the speaker chassis and is provided with a number of tappings to give different step-down ratios. It will be found, in the case of any particular speaker, that the reproduction is better on one pair of tappings than on the others. This is because with that particular winding the speech coil is more nearly " matched " to the impedance of the output valve.

Matching the Speaker Circuit to the Output Valve.—With the conventional method of transformer coupling, the loudspeaker to the anode circuit of the output valve, the speech coil is isolated from the D.C. component of the anode current. Since the impedance of the speech coil is very low, it would, in any case, be quite unsuitable for direct connection in the valve circuit, as was common practice in early receivers employing high resistance inductor or moving iron speakers. To secure maximum transfer of power from the valve to the speaker, the transformer windings must be selected so that a load equivalent to the optimum valve for the particular valve in use is secured. The impedance of the speech coil, of course, varies with the frequency, but for the purpose of determining the transformer ratio it is sufficiently accurate to consider it as twice its ohmic resistance.

If the transformer has a step-down ratio of $n : 1$ (i.e. n times as many turns on the primary as on the secondary), then a voltage E across the primary produces a voltage of E/n across the secondary; and if I is the current through the primary, the current through the secondary is nI. Thus the ratio of the voltage to the current, i.e. the effective resistance, of the primary is n^2 that of the secondary. If the impedance of the speech coil is K ohms, this is equivalent to a load on the valve anode circuit of n^2K ohms, which, for the best performance, should be equal to the optimum load of the valve (see Fig. 4). For instance, suppose we have a speaker with a speech coil resistance 8 ohms

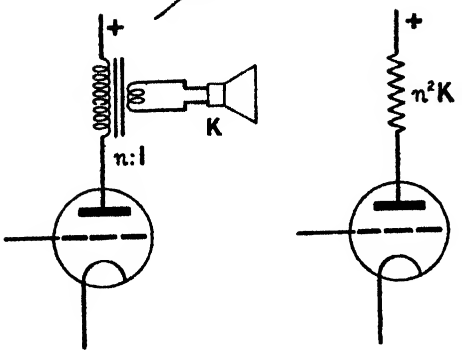


Fig. 4. — Equivalent Circuit of Transformer Coupled Loud-speaker.

corresponding to an impedance of approximately 16 ohms coupled to an output valve which has an optimum load of 3,600 ohms, then the transformer ratio should be—

$$\sqrt{\frac{3600}{16}} = 15:1$$

In the case of two valves in push-pull output stage, the transformer ratio is $\sqrt{\frac{2 \times \text{optimum load of one valve}}{\text{speaker impedance}}}$

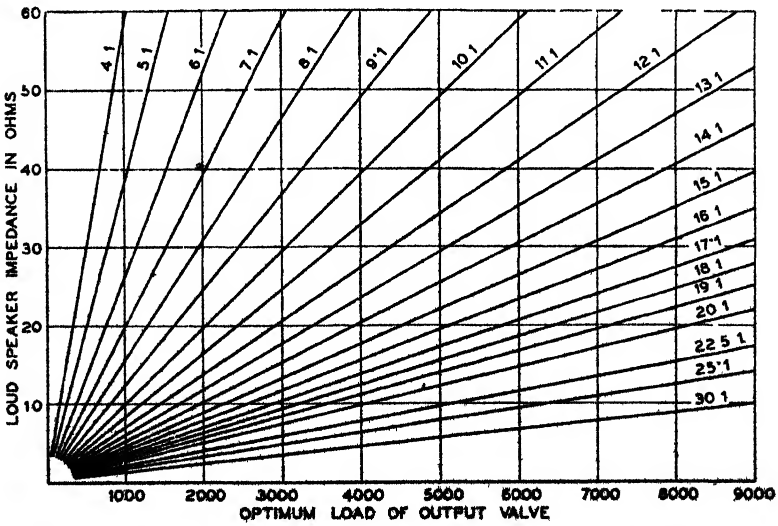


Fig. 5.—Transformer Ratios For Coupling Speaker to Output Valve.

Fig. 5 shows a chart from which the transformer ratio can be read off for any speaker with speech coil up to 60 ohms, and valves with optimum load up to 9,000 ohms. To use the chart for push-pull connected valves, the circuit must be considered to be that of a single valve with twice the rated optimum load of one valve. If two valves are in parallel, the circuit can be considered as that of a single valve with half the normal optimum load.

Baffles.—It is common experience that if a cone speaker is removed from its case, the sound output is greatly reduced and some of the low notes may disappear altogether. When the cone of a moving coil speaker is moving forward, the air in front of it is compressed while the air at the back of the cone is being rarefied, and *vice versa*. Thus, points in the air which are adjacent to each other, but separated by the thickness of the cone, are in opposite conditions of strain. If movement of the air round the edges of the cone is not restricted, these opposite pressure changes tend to neutralize each other, and particularly at low frequencies the sound output will be very small. This trouble can be cured by increasing the length of the air path between the front and back of the cone. One method of doing this is to mount the speaker chassis on a large, flat board, with a hole cut in the centre about the size of the mouth of the cone. Baffles of this type are used in a variety of forms. The objection to them is their size and difficulty of accommodation. The cabinet in which most speakers are housed and which is usually lined to prevent internal resonance, serves the same purpose as the baffle and at the same time affords protection against damage from outside.

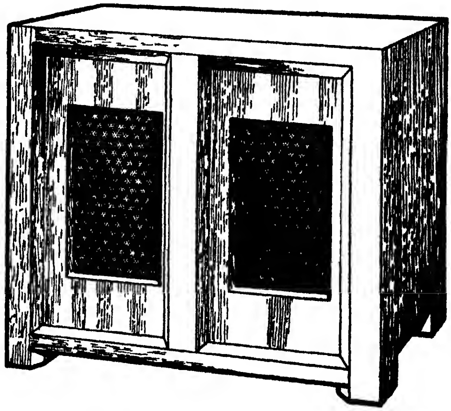


FIG. 6.—CABINET FORM OF LOUDSPEAKER.

Types of Speakers in General Use.—The great majority of speakers operated from radio sets are built into the cabinet

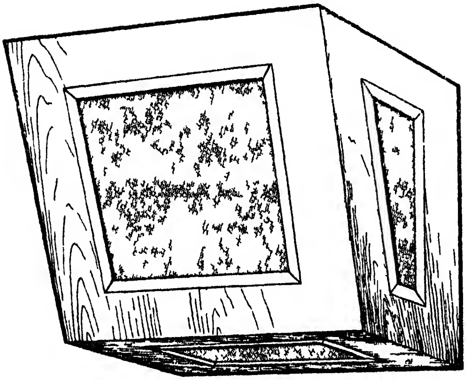
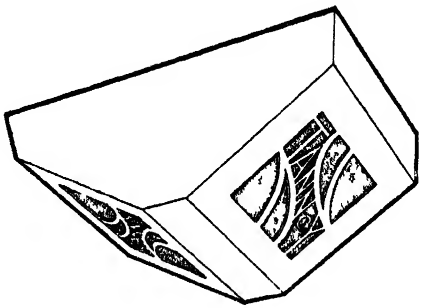


Fig 7 (*Left*)—Fitted Form of Cabinet Speaker For Above Head Level Mounting

Fig 8 (*Below*)—Indoor Suspension Type of Loudspeaker in Enclosed Cabinet for Distributing Sound over a Large Area (*Tannoy Products*)



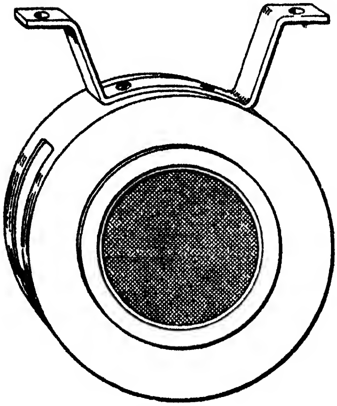
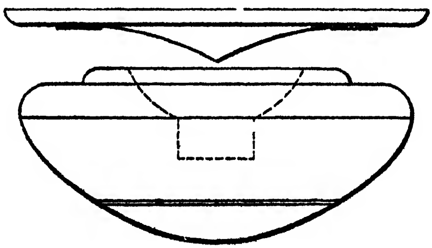


Fig 9 (*Above*)—Industrial Speaker Designed For Offices, Shops, Warehouses, Etc

Fig 10 (*Right*)—Bowl Type of Speaker For Ceiling Mounting (*Tannoy Products*)



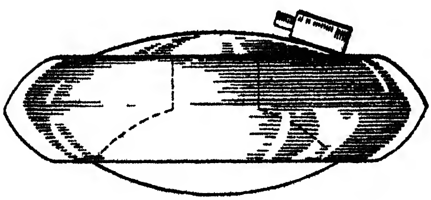


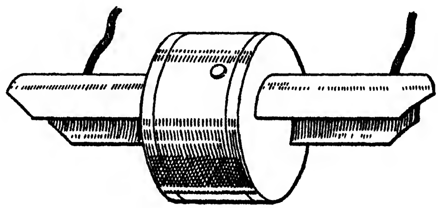
Fig 11 (*Left*)—Another Form of Bowl Speaker for Cable Conduit Suspension

which houses the complete receiver. The cabinet is designed to provide good acoustic properties with pleasing appearance, and is often the most artistic piece of furniture in the room where the set is used. Speakers in separate cabinets are usually employed with domestic receivers only when an additional point has to be fed from the same set, usually with a switching device to enable the extension speaker to be cut out when not required.

Public buildings demand units of more ambitious design and special types of loudspeakers are made for industrial use. A few typical examples are illustrated :

For wall mounting above head level, inclined types of cabinet speaker are frequently employed for the purpose of directing

FIG. 12.—BEAM DISTRIBUTION SPEAKER.



the sound downwards without tilting the cabinet (Fig. 7). Other forms are designed in shape to fit the corner of a room and so occupy the minimum of space. Fig. 8 shows a suspension type of speaker which includes two eight-inch cones mounted at an angle so that sound can be distributed over a large area. Bowl type speakers depart rather from the commonly accepted designs and are installed in buildings where appearance and performance are first considerations. Facing the cone (Fig. 10) is a scientifically designed reflector from which the sound is distributed evenly in all directions. The base of the reflector can be mounted on a wall or ceiling or stood on a desk. Fig. 11 shows another form of bowl speaker in which the protruding cable terminal box enables the unit to be suspended by its own cable conduit or mounted on a suitable wall bracket so that when in position it is inclined at an angle of 30 degrees. This unit is intended for industrial use on exposed locations for which the case is specially designed. The industrial type of speaker shown in Fig. 9, includes a 10-inch permanent magnet moving coil chassis fitted into a metal drum container with a convenient mounting attachment and is suitable for office buildings, stores, shops, warehouses and the less noisy areas of a factory. The

beam distributor unit of Fig. 12 caters for the special requirement of providing two-way sound distribution over a long narrow path and is employed for railway platforms and similar conditions where speech messages have to be confined to a selected area.

Dual Loudspeakers.—Although development in speaker design has reached the stage where a single unit will give reproduction quality which satisfies all but the most critical ears, it has been found that to secure super-quality necessitates the use of more than one speaker because it is difficult, if not impossible, to construct one unit which will give a level response over the whole audible range. Consequently, in installations which can stand the additional cost, dual speakers are frequently used. A frequent combination is that of two moving coil units with different sized diaphragms, the large one reproducing more fully the lower notes and the smaller accentuating the higher notes so that the response over the whole range is evened up.

A small speaker including a crystal driving element and called a " tweeter " is often used for extending the upper frequency range. This unit includes a small diaphragm which vibrates through the motion of a peizo-electric crystal. It will be recalled that certain crystalline substances of which Rochelle salt is an example, exhibit the property of deformation in certain directions when a difference of potential is applied between the crystal faces. If one part of the crystal is fixed, alternating potentials applied to the faces will cause the free end to vibrate and produce sound from the cone distributor to which the crystal element is attached. This is purely an electrostatic type of reproducer. It is isolated from direct potential in the valve output circuit by condensers as shown in Fig. 13. The potentiometer provides adjustment for the tweeter output. The use of peizo-electric crystals is dealt with more fully in the section on pick-ups.

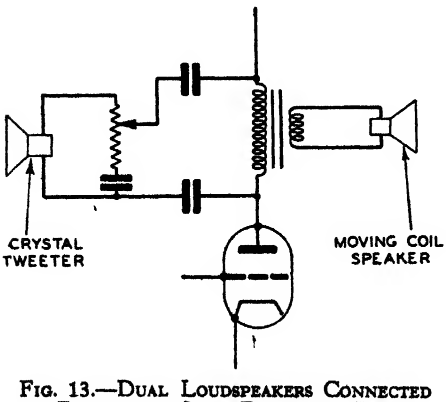


Fig. 13.—Dual Loudspeakers Connected to Extend the Line Frequency Range.

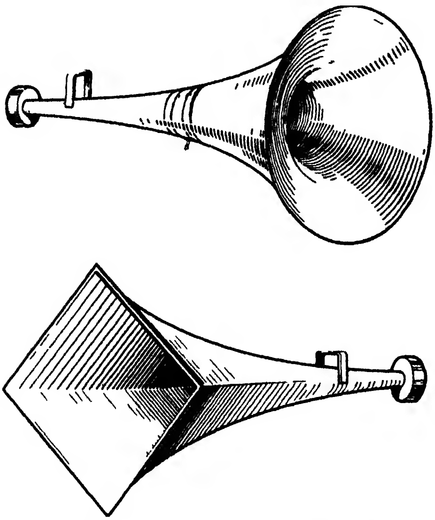


FIG. 14.—TYPES OF HORN SPEAKER.

Public Address Equipment

Horn types of speaker, singly, or in groups and of the "exponential," or re-entrant form are employed for use in outdoor conditions where directional projection of sound is required. These speakers have a small concave metal diaphragm about two inches diameter in the throat of the horn. In front of the diaphragm is a phase corrector which constricts the air space and is designed to ensure that sound from all points on the diaphragm traverse the same length of path to the horn and emerge in phase so that a good frequency response is maintained. The horn does not amplify the sound, but modifies the sound pressure to secure sound projection in the required direction. The wide use of these speakers for outdoor installations necessitates design to avoid trouble from rain or dust and to prevent displacement of the coil from the centre of the gap through external shock. Fig. 15 shows a multibeam assembly unit for use in theatres, etc. A bank of nine, specially matched, speaker units are mounted so as to give a correct frequency balance over an angle of about 30 degrees, resulting in a well maintained upper scale response with adequate bass. The metal cabinet has a tilt of 10 degrees to give upward or downward

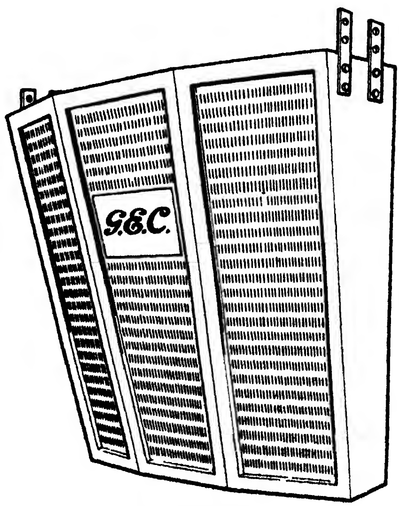


FIG. 15.
MULTIBEAM SPEAKER ASSEMBLY.
(The General Electric Co., Ltd.)

projection and provision is made for wall mounting or chain suspension. Though sensitive to inputs of one or two watts, a single assembly can handle inputs up to thirty watts without distress.

Extension Speakers

Receivers are frequently designed with provision for an extension speaker. It is usual for a switch or plug to be included so that the extension speaker can be switched off when not required. Unless some additional component is included, it is clear that the optimum conditions of matching previously referred to, cannot be fulfilled in both cases, i.e. with either one or two speakers in use. To prevent mismatching when the circuit is switched from one condition to the other, a resistance equal to the extension speaker impedance is automatically put in circuit when the extension speaker is withdrawn so that the circuit conditions remain almost the same. Parallel connection of speakers is usual. In public address equipment, the groups of speakers are often some distance from the amplifier and the voltage loss in the cables has to be considered. Since this cannot be reduced below a certain level without large-sized cables, which would be too expensive, the proportion of the output voltage lost in the cables is kept within reasonable limits by suitable choice of the transformer ratios at the points where the speakers are installed, as this provides a means of altering the equivalent impedance of the speakers to secure optimum efficiency.

Volume Control

Where several speakers in different rooms are fed from the same set, individual volume control is desirable so that the output of one speaker can be adjusted without affecting the others. The simple arrangement of a variable series resistance which is sometimes used is not very satisfactory from the point of quality of reproduction. The impedance of the speaker speech coil is lower at low frequencies, so that in the lower notes, the series resistance tends to absorb a greater proportion of the total voltage across the speaker and cut off, or attenuation of bass notes is likely to occur. The alternative of potentiometer control with one terminal of the speaker connected to the slider

has its disadvantages also. As the potentiometer resistance is a shunt to the speech coil, it must be fairly high, otherwise it will divert too much power from the speaker. Under these conditions, there will still be a high resistance in series with the speech coil when the volume is turned down so that the same objections as in the case of the series resistance still exist. A tapped choke offers a third and better alternative, but gives only stepped degrees of volume control and is expensive. These objections make it preferable, in the case of single speaker sets, to incorporate the volume control in the amplifier circuit to adjust the overall gain rather than use an attachment to the speaker circuit.

Phasing

If more than one speaker is connected to the same power circuit, care must be taken to see that all the speech coils are connected the same way round so that the diaphragms all move in the same direction at the same instant, otherwise the vibrations from any unit whose terminal connections are reversed will be out of phase, and the total volume of sound will be reduced. Generally, the polarity of the coil is marked or indicated by coloured terminals. If not so indicated, the connections will have to be identified, though as a general rule with speakers of identical form, the position of like terminals will be the same.

However, identity of connections can be confirmed either by connecting the speech coil to a battery to find out which way the diaphragm moves for a given polarity; or through aural detection by trial. For the latter type of test, with one speaker operating, the result of switching the second speaker on is observed. If the sound is reduced, the phasing is incorrect and one of the speaker windings must be reversed. As this test is most easily carried out with a note of constant low frequency, either a constant frequency record and pick-up or mains hum can be employed as a convenient input signal. Sufficient coupling to the supply mains can be secured by connecting the winding of an intervalve transformer across the input terminals of the set with the volume control turned down. If this transformer is then placed near the mains transformer, sufficient hum will be picked up for the test to be carried out.

MICROPHONES

The microphone converts sound waves into variable electric currents. Consequently, it performs the operation of the telephone headphones in reverse. Its two main uses are:

(1) In public address equipment, to enable a person to address a large gathering of people under conditions where he would not otherwise be heard.

(2) To modulate the output of a radio-frequency oscillator for the purpose of enabling speech and music to be broadcast by radio. There are five basic forms of microphone.

Carbon Microphones

The oldest form of carbon microphone was employed in telephone circuits long before the days of broadcast transmission. The electrical resistance between two pieces of carbon is reduced when they are compressed together and increased when the pressure is withdrawn. By using carbon in the form of a number of granules, the surface area affected by such pressures is greatly increased and the device made more sensitive to pressure changes. Fig. 16 shows the elements of the carbon microphone as a sound converter. Sound waves striking the diaphragm cause it to vibrate and transmit pressure changes to the carbon granules which are connected in circuit with a low voltage battery and the primary winding of a step-up transformer, through which the current changes are stepped up before being passed on to the output circuit.

In a diminutive form, known as the button type microphone, the carbon granules are compressed by a type of piston which forms one electrode and which is rigidly connected to the centre

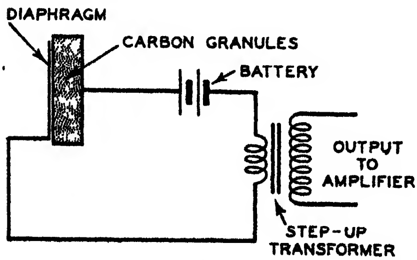


Fig. 16.—Principle of the Simplest Form of Carbon Microphone.

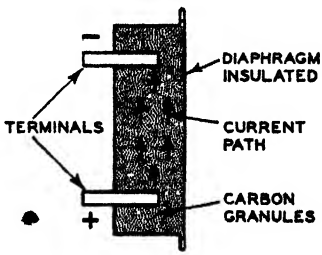


Fig. 17.—Principle of the Transverse Current Carbon Microphone.

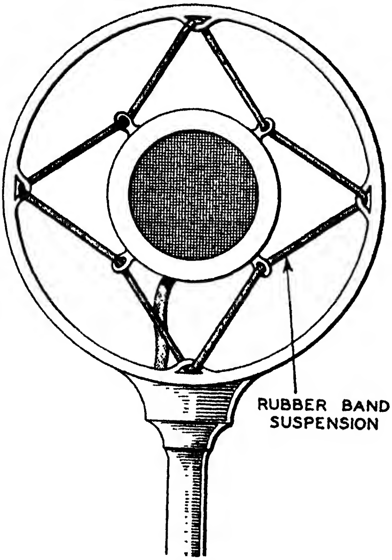


FIG. 18.—TRANSVERSE CURRENT TYPE OF MICROPHONE

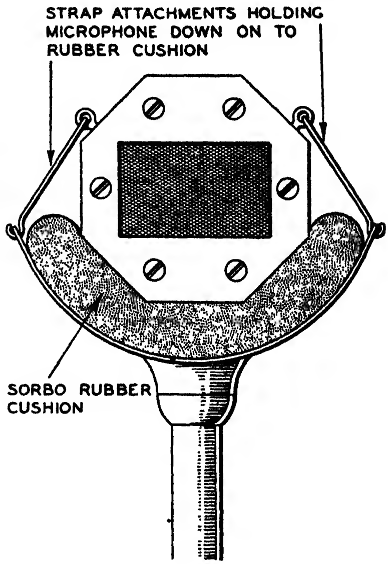


FIG. 19.—MARCONI-REISS TRANSVERSE CURRENT TYPE MICROPHONE

of the diaphragm. In the transverse current type of microphone (Fig. 17), current does not pass through the diaphragm which is of mica, or other insulating material. Two electrodes connected externally to terminals are embedded in the carbon granules and though the diaphragm still causes current changes by compression, the current flows in the direction of the plane of the diaphragm.

About 4–6 volts from dry cells is sufficient for the average carbon microphone. Higher voltages cause burning of the carbon points and produce increased background noise. The carbon microphone is a sensitive device, but its characteristics are not very constant and it produces a good deal of background noise, consequently it is used where sensitivity with intelligibility of reproduction is required rather than good quality. In time, the continual pressure changes make the carbon particles pack together and the resistance progressively decreases. It can be temporarily restored by tapping the casing. This type of microphone should be installed with the diaphragm vertical. A minor disadvantage is the continuous drain of current on the battery. In spite of these disadvantges, the fact that the device

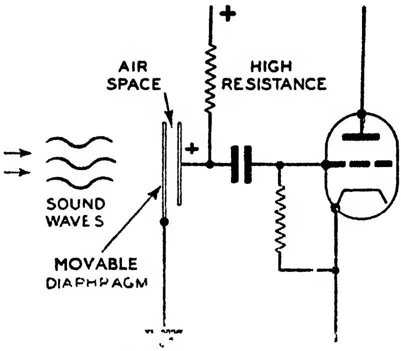


FIG. 20.—PRINCIPLE OF THE CONDENSER TYPE OF MICROPHONE

is simple, robust, cheap, and reliable will probably enable it to continue in use in spite of the superior characteristics in electrical and acoustic performance of alternative types of sound convertor.

The Condenser Type of Microphone

The condenser type of microphone depends for its operation on the fact that the voltage across an electrical condenser which holds a constant charge depends on the capacity of the condenser (see Fig. 20). If the capacity is increased, the voltage across the condenser falls; if it is reduced the voltage rises, always assuming that the charge remains unchanged. The condenser microphone consists essentially of two metal plates, one of which is suitably suspended and of sufficient flexibility to vibrate at right angles to its plane when sound waves strike it. The other plate is fixed in position in the body of the instrument. These two plates which are separated by an air space form a small condenser of about 0.0003 mfd. capacity. The fixed plate is connected through a high resistance of several megohms to a battery which serves to maintain a charge upon it and make up for loss due to insulation leakage. The diaphragm is earthed.

When sound waves strike the diaphragm, its movement towards and away from the fixed plate varies the capacity of the condenser and the corresponding voltage changes are passed on to the amplifier through a small fixed condenser connected between the fixed plate and the grid of the first valve. Since the capacity changes due to the movement of the diaphragm are very small, the voltages generated are feeble and compared with the carbon microphone, the sensitivity of the device as a sound converter is low. For this reason, a preliminary stage of valve amplification is required before the signals are passed on to the main amplifier. Unlike the carbon microphone which usually has a resistance of a few ohms, the condenser instrument is a high impedance device. The frequency response however, is

much better and there is no background noise. Neither is there any drain on the battery supply. Though simple in principle, the design of a practical instrument involves several factors which cannot be detailed here, notably in the introduction of suitable damping to minimize the natural resonance of the diaphragm.

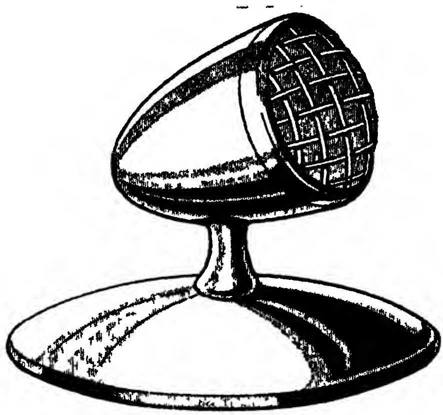


FIG. 21.—DESK TYPE OF PRESSURE-ACTUATED MICROPHONE.

The Moving Coil Microphone

In principle, the moving coil microphone differs little from the permanent magnet moving coil loudspeaker and the fundamental arrangement of a coil of a few turns of wire attached to a diaphragm and suspended in the field of a magnet is the same. This device is a low impedance sound convertor. When sound waves strike the diaphragm, the movement of the coil in the surrounding magnetic field generates small voltages by induction and these voltages are passed on to the first valve of the associated amplifier through a step-up transformer. The moving coil microphone combines some of the merits of both the carbon and condenser types. It has the high sensitivity of the former without its corresponding defect of background noise and the frequency response is good. Unlike the condenser type of instrument, there is not the same possibility of trouble due to insulation leakage through atmospheric moisture and the output is high enough to enable it to be used with a fairly long transmission line without a preliminary valve amplifier.

Crystal Microphones

Piezo-electric crystals are employed as sound converters in microphones of special design and have some advantages over other types of instrument. Two crystals, in the form of thin plates, are generally employed with suitable electrodes and are arranged so that the air pressure tends to compress one and extend the other so that the voltages produced by each crystal

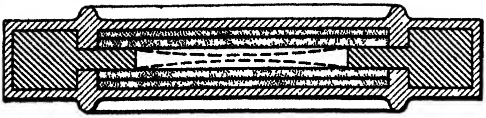


FIG. 22.—ENLARGED SECTION OF ROTHERMEL-BRUSH PIEZO-ELECTRIC SOUND CELL TYPE OF MICROPHONE. (Dotted lines show direction of crystal deflection under pressure.)

are in phase with one another and therefore additive. The crystal elements usually have an electrostatic capacity of the order of 0.005 mfd. so that as a sound converter, the impedance is fairly high. It is possible, however, to adjust the value of the impedance to some extent by series or parallel connection of the crystal elements. Unless the connecting leads are short, the high impedance of the instrument will call for a pre-stage of amplification.

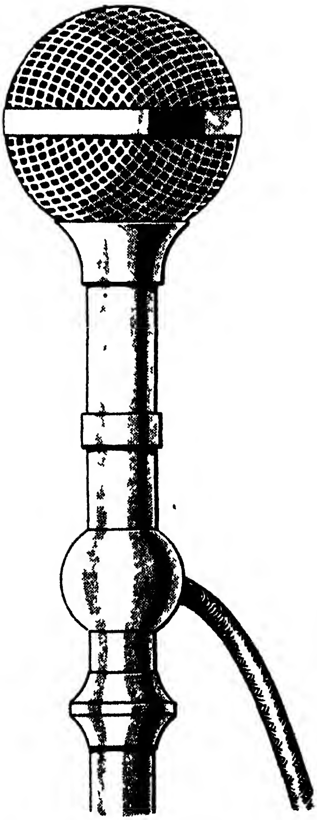


FIG. 23.—GRILLE TYPE PIEZO-ELECTRIC MICROPHONE.

A notable feature about crystal microphones is the fact that mechanical vibrations which reach the instrument, other than through the air at the crystal face, cause the crystals to move in the same direction so that the voltages generated by the disturbance are in opposition and thus cancel each other. For this reason, vibration of the support due to handling, footsteps, etc., do not cause noises from the speaker.

Two forms of crystal microphone are in general use. In the first, called the sound cell type (Fig. 22), sound waves impinge directly on the crystal. The two crystals are set in a housing with internal spring mounting to reduce mechanical shock. In the second, a diaphragm type, the crystal is mechanically connected to and stressed through the coupling with the diaphragm. A typical form of crystal microphone is shown in Fig. 23 and is a grille type in which the casing is constructed of a finely woven brass screen, reinforced with a horizontal

metal band to give rigid support to the mounting of the sound cell. The response is non-directional so that sound waves coming in any direction can pass through the casing to the sound cell. Crystal elements are also incorporated in stand and table type mountings, many of which are similar in external appearance to other forms of microphone.

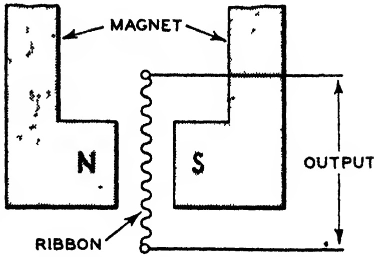


FIG 24.—PRINCIPLE OF THE RIBBON OR VELOCITY TYPE OF MICROPHONE.

Ribbon-type Microphones

In the previously described instruments, voltages are generated by air pressure changes and they are known as pressure type microphones. The ribbon type microphone is an example of the class known as velocity microphones, because the inertia and suspension of the moving parts are such as to enable them to follow the changes in velocity of the air movements caused by the sound waves. Voltages are generated in the same way as in the case of the moving coil microphone, i.e., by induction through the movement, to and fro in a magnetic field, of a narrow thin flexible corrugated metal ribbon (Fig. 24). Since the moving member consists of a single conductor, the output voltage is very small with a correspondingly low impedance, usually a fraction of an ohm. This type of instrument is less sensitive than the moving coil type, but has a good frequency response. Owing to the low sensitivity, the permissible length of cable between microphone and amplifier is less than with the moving coil instrument and an impedance matching transformer is preferably mounted quite close to the instrument. The ribbon microphone is directional in its response, and the source of the sound should not be too near the instrument, if good reproduction is

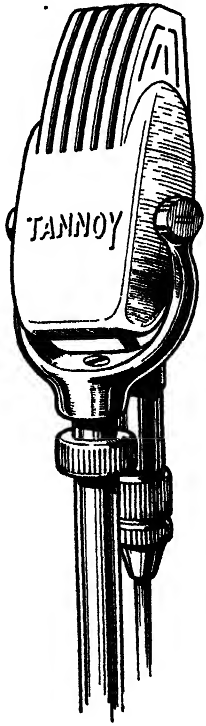


FIG. 25.—RIBBON TYPE MICROPHONE. (*Tannoy Products.*)

to be secured. In outdoor positions, protection is required against wind which causes the ribbon to vibrate and produces a disturbance known as " flutter "

Feedback

The directional properties of a microphone indicate the angle within which it is able to pick up sound without loss of sensitivity, or quality of reproduction. If the relative positions of the microphone and loudspeaker are such that the amplified sound can reach the microphone, feedback will occur; part of the output will continually reinforce the input signals, and the amplification will build up to a high value, become unstable and produce a continuous howl. In certain cases, where the acoustic properties of the building are such that echoes may cause feedback, the use of a microphone with a restricted angle of pick-up may be an advantage.

Microphone Leads

The connecting leads to the microphone are particularly prone to pick up electrical disturbances from neighbouring circuits. Lead-covered twin bell wire, rubber and cotton insulated, with the sheathing continuous and efficiently earthed is suitable for permanently connected indoor installations. Twin wires are preferably twisted together, since any currents induced from neighbouring conductors are then, to a large extent, neutralized. Flexible connections are best made with specially designed cable comprising a central conductor surrounded by p.v.c. dielectric and a woven flexible copper outer conductor to form the lead at earth potential. This copper sleeving has a woven silk or fabric covering to prevent possible noise if the metal sleeving makes contact with metallic objects.

Condenser and crystal microphones being of very high impedance are susceptible to electro-static pick-up, while the low impedance instruments, the moving coil and ribbon types, are liable to disturbances through electro-magnetic induction. Shielding is adopted to short circuit any external alternating electric or magnetic fields and prevent them from reaching the conductors inside the shield. In the case of high impedance pick-ups, the screening must be sufficiently low in resistance to avoid any appreciable potential difference existing between any points in its length.

PICK-UPS

The term pick-up is generally intended to imply the kind of device which enables sound to be reproduced from disc records. It is, however, also used in a much wider sense to include (i) converters which enable sound to be reproduced from other forms of record, e.g. wire tape; (2) Means for measuring mechanical vibrations which are often below the audible range, e.g. in rotating machinery. Even microphones are sometimes referred to as sound pick-ups. We shall confine our attention here to disc record converters. The two important classes of pick-up are the magnetic type and the crystal type, and though others have been used they are less extensively adopted.

In both types of pick-up, the vibrations recorded are transmitted to the converter through the needle which follows the undulation of the record track. When the record is rotated, the needle is forced to vibrate about its support, in a side to side movement, by the irregular surface of the side of the groves in the record. The ear has a very variable response to sounds of different pitch, and to produce the same level of loudness over the whole scale would require much greater power in the low notes. Consequently, if the pick-up has an even response to notes of all frequencies as a sound converter, the amplitude of vibration of the needle would have to be very large for low notes. Not only would it not be possible to accommodate the necessary width of groove on the track without great complication, but there would also be trouble in preventing the needle jumping out of the groove with such large movements. To avoid these difficulties, the pick-up has to be designed to accentuate the bass notes and have a frequency response which rises towards the lower end of the scale, so that smaller amplitudes of vibration are required to produce the same level of sound. Owing to the much larger vibration of the moving part, the voltage generated by a pick-up—about 0·5 to 1 volt—is much greater than that from a microphone

The Magnetic Pick-up

The principle of the magnetic pick-up is shown in Fig. 26. A pivoted armature is mounted in the narrow gap of a powerful magnet having recessed poles to accommodate a separate coil in which the output voltages are generated. The needle is clamped by a screw into an extension of the armature. When

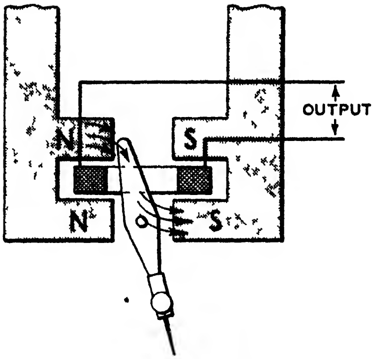


FIG 26.—PRINCIPLE OF THE MAGNETIC PICK-UP.

the armature is in the central position, the magnetic flux through the pick-up coil is symmetrically distributed, but when the armature moves towards either side, the flux, through the pick-up coil changes and induced voltages, are passed on to the amplifier circuit. The armature is located in position by rubber dampers, which limit the extent of its movement and provide the restoring force tending to bring the armature back to the centre position. The nature of the winding of the pick-up and its impedance varies considerably in different makes. The generated voltage is increased by having a coil with a large number of turns of wire and is then suitable for direct connection to the amplifier, but the high impedance tends to increase capacity losses in the connecting cable which must be kept short. A coil with a smaller number of turns of thicker wire gives a less sensitive, but more robust device, which requires a matching transformer to couple it to the valve amplifier.

The Crystal Pick-up

Piezo-electric crystals have been referred to briefly in Chapter II and also in connection with microphones and loudspeakers. We will digress here a little to explain more fully their operation since these devices are employed in pick-ups, possibly even more extensively than in microphones or loudspeakers.

When compressed, or stretched in certain directions, piezo-electric crystals show a difference in voltage between parts of their surface. Rochelle salt is the substance which shows this property best. It is a type of crystal which is perfectly stable in air, but being soluble in water has to be given a protective coating to preserve it against external damage. A Rochelle salt crystal looks very much like the roof of a shed (Fig. 27 (*a*)). There are three mutually perpendicular directions through the centre of the crystal which are known as the axes and have interesting properties which we cannot stop to describe here. Sections of the substance which are cut out of the crystal so that

their lengths make an angle of 45 degrees with the *b* and *c* axes, have been found to show the piezo-electric effect most markedly. Such a section is shown in Fig. 27 (*a*). If a piece of the crystal like this is compressed at its ends, a difference of potential will appear between its upper and lower faces (Fig. 27 (*b*)). When the same piece of crystal is stretched, the polarity of the voltage will be reversed (Fig. 27 (*c*)). If now these slices of crystal are made very thin and cemented together with an electrode between them, with the two outer faces connected to a common terminal, the potentials developed by the crystals when the continuation is bent, as in Fig. 27 (*d*), will assist one another because the upper one is then stretched and the lower one compressed. By using a " bender " form of crystal in this way, it is possible to increase the voltage generated by a given deflecting force. An important advantage gained from a composite crystal of this type is that some of the less desirable features of single crystals, such as temperature effects can be balanced out. In a somewhat similar way, two cemented crystals can be employed to generate voltages when a twist is applied to them.

These are the principles employed in the crystal pick-up, the needle movement constituting the deflecting force, causing deformation of the crystal element and generating the voltages which are passed on to the amplifier.

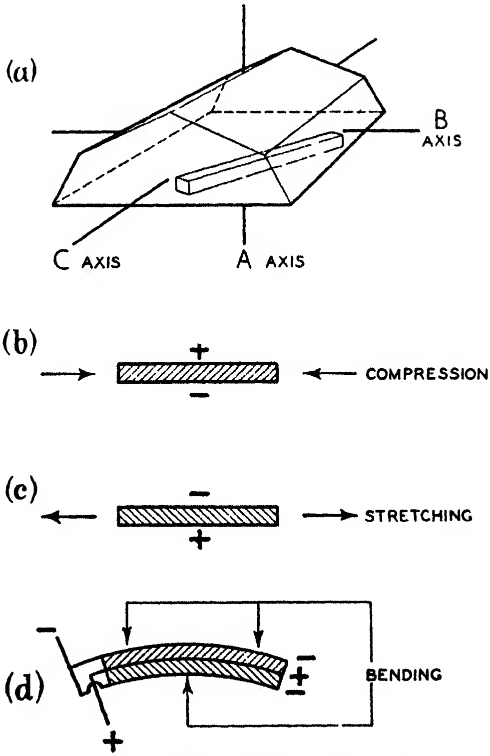


FIG. 27.—PIEZO-ELECTRIC CRYSTALS.
(a) Natural crystal of Rochelle salt.
(b) to (d) Potentials due to straining.

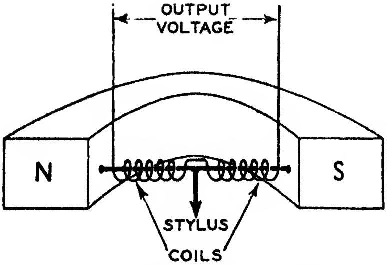


FIG. 28.—PRINCIPLE OF THE MAGNETO-STRICTION PICK-UP.

The crystal pick-up is a high impedance device. It is more sensitive than the magnetic type and has a better frequency response, but it is rather fragile and accidentally dropping the pick-up on to the record frequently fractures the crystal.

Other Types

Moving coil types of pick-up are in use. Just as the moving coil speaker is superior to the moving iron instrument, so the moving coil pick-up is claimed to be superior to the type of unit previously described. The moving coil unit is obviously much more difficult to design. Another kind of pick-up is the magneto-striction type. Certain magnetic materials, in the form of a wire or rod, in the presence of a magnetic field show variations in magnetic properties when subjected to torsion or strain. This means that when the material is stretched, compressed or twisted, the magnetic flux through it changes. This property, which is known as magneto-striction, has been applied to the design of a special form of pick-up which has a size smaller than a crystal element and claims for low distortion, robustness and wide frequency response.

The magneto-striction element is a nickel wire about 0·020 inch diameter mounted between the poles of a magnet (Fig. 28) with the pick-up coils, each consisting of about 100 turns, wound round the two halves of the torsional member with the stylus protruding from the wire between the pick-up coils. A preliminary strain is given to the wire by twisting and it is then fixed between the pole pieces. This initial strain ensures that in the subsequent movement of the stylus, the voltage generated is proportional to the amplitude of the trace on the record. In its movement, the stylus increases the strain on one half and reduces it on the other half, the windings being such that these effects assist one another. A push-pull effect is thus obtained, the result of which is to cancel out even harmonics and materially reduce the distortion. Together with the small coil diameter, this greatly reduces the interference from external fields.

Scratch Filters

The rubbing action of the needle on the disc surface and the mechanical resonances of the armature suspension result in a high pitched background or rustling noise known as " scratch " which is not wholly due to the friction between the needle and the disc. These disturbances have frequencies round about 4,000. To reduce surface noise and subdue resonances, a shunt circuit is often connected across the pick-up terminals. It usually consists of a condenser of about 0 006 mfd. in series with a resistance of about 10,000 ohms. This constitutes what is known as a high pass filter because it shunts all frequencies above a certain range and prevents them reaching the amplifier. A band-pass filter is, of course, better because this will shunt the scratch frequencies, but still allow the high notes recorded on the disc to get to the amplifier. Such a filter is shown in conjunction with a volume control in Fig. 29.

Volume Control

The volume control will vary with the type and impedance of the pick-up, and the maker's recommendation should always be followed because an unsuitable value of volume control may seriously impair the performance of a pick-up by affecting its frequency response. A potentiometer type of control is usual, one side being earthed and the slider feeding the signal output circuit. In the volume control shown in Fig. 29, the arrangement is such that as the volume is reduced extra resistance is inserted in the signal lead so as to maintain a constant impedance in the pick-up circuit. When incorporated in radio sets, the pick-up circuit is controlled by a two-way switch in the detector or low-frequency circuit so that the high-frequency portion of the receiver is switched off when the pick-up is brought into circuit. The volume control is preferably a graded resistance wound on a tapered former to prevent all the adjustment coming too near one end of the scale. A uniform winding has the effect of cutting off too much bass. Circuits including condensers are also sometimes added to the volume control to correct any change in frequency response.

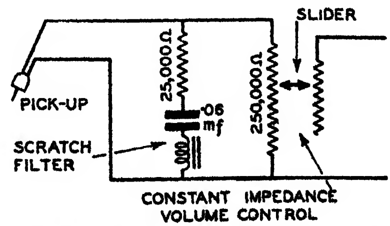


Fig. 29.—Scratch Filter and Volume Control for Pick-Up Circuit.

Tracking Arm

Theoretically the pick-up should be tangential to the record groove, but as this would need a very long arm it is clearly impracticable and a compromise has to be adopted. The manufacturers always supply templates to ensure that the pillar of the tracking arm is fixed in the best position relative to the turntable. Setting up the tracking arm must be carefully done as any error in position will lead to destructive wear on the record. The pillar must be mounted at the right height to secure the correct angle between the needle and the record surface.

The support of the tracking arm should preferably be mounted on ball bearings to secure minimum friction without looseness. The carrier arm must be balanced so that most of the weight of the pick-up is taken off the record and there is just sufficient pressure to secure good tracking.

Screening

The same precautions apply to pick-ups as to microphones, since, although the generated voltage is much higher, the chief source of disturbance, the driving motor and the leads connected to it are very close to the pick-up. The motor case should be totally enclosed in an earthed metal case. Commutator motors frequently require condenser interference suppressors comprising two equal condensers in series across the brushes, with the centre point earthed. The tracking arm and supporting pillar should also be earthed. Low capacity, metal screened cables, as employed for microphones, should be used for connections to the pick-up and the leads to the scratch filter and volume control kept as short as possible.

CHAPTER XVIII

POWER SUPPLY FOR RADIO SETS

A SOURCE of electric current is required for every radio receiver and transmitter to provide power for signal amplification. Direct current is needed for the anode and screen grid circuits of the valves and either direct or alternating current for their filaments or heaters. In receiving sets which include something more than the simplest arrangement for reception, power may be needed for other purposes, such as turntable motors, record changers in radiograms, tuning dial lamps, and automatic tuning motors. Transmitters also require power to maintain the electrical oscillations necessary for signal radiation. For all such purposes, a mains supply is to be preferred because it requires no maintenance from the user and ample power is always available. Not all users are, however, fortunate enough to have a mains supply and there are also many instances such as portable sets which must rely on batteries.

For mains supply A.C. is always preferable, owing to the ease with which it can be transformed, or rectified, to secure any desired voltage either A.C. or D.C. D.C. mains are often supplied through mercury arc rectifiers and may contain considerable electrical disturbances which are troublesome to eliminate. In addition, some D.C. supplies have the positive side earthed. Even if only D.C. mains or batteries are available it is still possible to employ an A.C. mains set by the use of a rotary transformer, but most users will probably not be prepared to go to the expense of such a converter. The power supply which will be employed will, therefore, depend firstly on the amenities of the premises where the set is installed and secondly, due to the present restrictions of production on the type of receiver which is commercially available. Battery-fed receivers can, of course, be used anywhere. If D.C. mains are installed, the choice lies between a D.C./A.C. set, a battery

set with H.T. eliminator or an A.C. mains set with a rotary converter. It is not practicable, without structural alteration, to operate a mains set direct from batteries or *vice-versa.*

Batteries

A battery-fed receiver requires two separate electrical supplies, an accumulator for the valve filaments and a higher voltage (H.T.) battery usually of dry cells. As the current taken by the filaments is much greater than that required in the valve anode circuit, it is impracticable to use one battery for the two circuits. As the theory of operation and maintenance of the secondary cell is dealt with in Chapter XIX, little need be said about the accumulator other than to stress the necessity for adequate maintenance and the following points are therefore repeated here:

An accumulator is easily ruined if allowed to remain long in the discharged condition. The level of the acid should be maintained to just cover the plates by the addition of distilled water to replace that driven off during charging and the terminals should be kept scrupulously clean. Failure of a receiver to function at all is often traced to dirty battery terminals. Sometimes they are allowed to get so corroded that the terminals can only be unscrewed by using force and the screwed portion then often breaks off and a good battery is rendered useless. The positive terminal, usually coloured red, should be kept lubricated with vaseline.

Some valves are also designed with low current filaments for operation from dry cells, but their use in this country is the exception rather than the rule. For small receivers where the total anode current does not exceed 15 milliamps or so, dry cell H.T. batteries give economically adequate life. They are usually provided with a separate section tapped every few volts below the H.T. negative giving adjustable voltages for grid bias. Small accumulator batteries for H.T. supply are ideal for good reception, but they are bulky, expensive and troublesome in upkeep, and these disadvantages are serious enough to restrict their use. For receivers having large output, dry cells may give too short a useful life and the quality of reproduction will deteriorate quickly. The choice then lies between an H.T. accumulator and a rotary machine.

The usual way of distinguishing the various leads to a battery set, though not universally adopted, is by coloured wander plugs. Red, yellow, green and black in decreasing order of voltage magnitude are used for the H.T. leads; black for the common H.T. and L.T. minus; pink for the L.T. plus, and brown, grey and white in decreasing magnitude for values of negative grid bias.

Fuses.—In all battery-operated sets where separate terminals are provided for filament and H.T. connections which the user has to remove when the accumulator is recharged or the H.T. battery renewed, the H.T. circuit should include a correctly rated fuse. The omission of a fuse and the accidental connection of the H.T. battery to the filament terminals means the destruction of the valve filaments and the costly business of replacing them all. Frequently a flash lamp bulb is used as a fuse, in which case it is important to remember that when a new one is required the replacement bulb must be of the same rating as the original one. Any flashlamp bulb will not do. Nor is the stamping on the cap, indicating its rating as a flashlamp, necessarily any clue to its suitability, or otherwise, as a fuse for the H.T. circuit of any particular set and should be noted only as a means of securing identity of replacement. If there is any doubt about the rating the maker's advice or publication on the particular receiver should be consulted.

Mains Supply

In the great majority of cases alternating current mains will be available for domestic receivers, and means must then be provided to secure direct current for the valve anodes and screen grids. This supply will also furnish the grid bias voltage by means of suitable cathode resistances. The valve cathode heaters will be supplied by A.C. from separate windings on the power pack transformer.

A.C. RECEIVERS

Half-wave Rectifiers

We will deal first with valve rectifiers because these are most generally used. The valve, a diode, has only a heated cathode and an anode. The cathode may be directly or indirectly heated from a low voltage winding on the transformer which forms the link between the set and the supply mains. A separate high

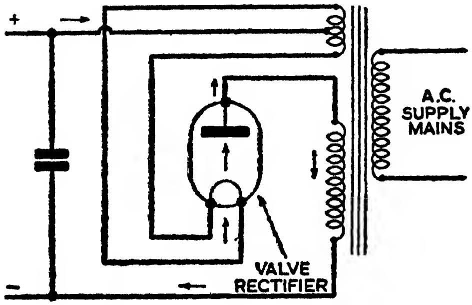


FIG. 1.—SIMPLE HALF-WAVE VALVE RECTIFIER.

The arrows show the direction in which the electrons move, which is opposite to that in which the current "flows."

voltage applies alternating potentials to the valve anode and since the valve as its name implies is a device which passes current only in one direction, current will pass through it during the time the anode is positive to the cathode. This is shown in Fig. 1 where the arrows indicate the direction in which the electrons can travel through the valve. This direction is opposite to the conventional method of expressing current "flow," which is from positive to negative. Thus every fiftieth of a second a spurt of current passes into the condenser which acts as a reservoir of current. The charge passes into the condenser only during one half of the alternating supply wave. During the succeeding half cycle when the anode is negative to the cathode, the current is completely cut off. When current is drawn off the condenser further current passes into it through the valve to maintain its charge, which is thus used to feed the valves of the receiver. The condenser evens out the current fluctuations between supply and demand and acts in the same way as a reservoir does in a water pumping system.

This process is known as half-wave rectification because the electrons can only pass through the valve while the anode is positive, and the other half of the supply voltage is wasted since it produces no direct current (Fig. 2).

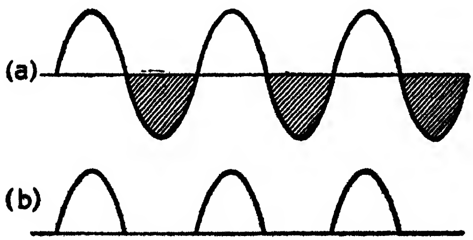


FIG. 2.—ALTERNATING VOLTAGES APPLIED TO THE VALVE THROUGH THE MAINS TRANSFORMER.

Pulses of current (b) are passed when the valve anode is positive. During the negative half of the alternating voltage shown shaded in (a) the current is cut off.

Full-wave Rectifiers

If we could have two such valves with their anodes connected to opposite ends of the high voltage secondary transformer winding, then current would pass through each valve in turn as the alternating voltage reversed, and both halves of the supply wave would be used. This is very much more efficient and leads to the arrangement shown in Fig. 3. In this diagram the full arrows indicate the direction in which the electrons pass through the valve when the top end of the secondary winding is positive. The dotted arrows show their

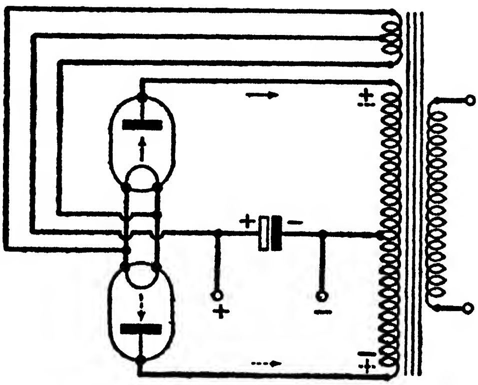


FIG 3.—DIRECT CURRENT OBTAINED FROM TWO HALF-WAVE RECTIFIERS EACH DRAWING CURRENT FROM THE SUPPLY IN TURN

This is termed full-wave rectification, because both halves of the alternating voltage wave are utilized.

direction when the mains voltage reverses, *i.e.*, when the bottom end of the transformer winding is positive. It will be seen that in both cases the condenser is charged in the same direction so that both halves of the supply voltage contribute to the production of direct current.

Now, in practice, this arrangement is simplified by having two anodes in a single valve with a common cathode with considerable saving in space. This is known as a biphase, or full-wave rectifier, and is always preferable to a half-wave rectifier for reasons which we shall see later. Fig. (4a) shows a full-wave rectifier with the full and dotted arrows showing the directions in which the electrons pass during the two halves of the voltage wave as in the previous figure. It will be noted from Fig. 4 (b) that in this instance the spurts of current into the reservoir condenser are twice as frequent as in the half-wave rectifier,

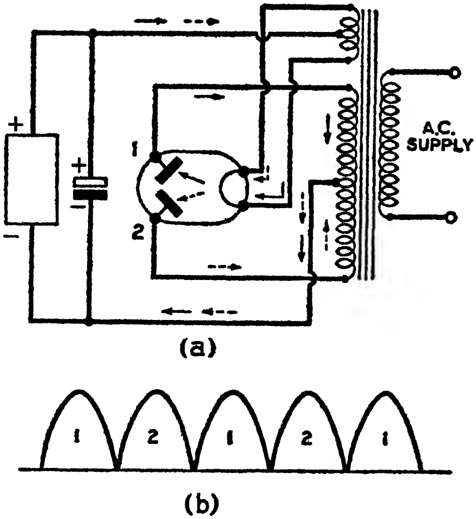


FIG. 4.—FULL-WAVE RECTIFICATION USING A SINGLE VALVE.

(a) How direct current is obtained by a rectifier valve having two anodes.
(b) The spurts of direct current passed into the condenser.

leading to a much more even and steady supply of direct current.

These circuits have some other interesting points. In the full-wave rectifier each half of the transformer winding is in operation in turn and only one half carries current at any particular instant. The currents in the two halves are in opposite directions and the nett effect is to cancel the magnetization of the core. In half-wave rectifiers the direction of the current through the high voltage winding is always the same, and the core is continuously magnetized in the same direction. This is liable to produce a distorted wave form and increase the difficulties of smoothing.

Another point to be borne in mind is that the heater winding of the rectifier valve becomes the high voltage or positive side of the direct current supply. Consequently, this winding cannot be used to feed any of the heater circuits of the amplifier valves in the receiver and it is not possible to economize on the transformer by using one low voltage winding for the two circuits. Half-wave rectification is employed on A.C./D.C. sets, but for receivers designed for A.C. mains only full-wave rectification is invariably used in view of its higher efficiency and simpler smoothing circuits.

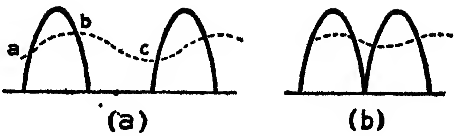


FIG. 5.—HALF- AND FULL-WAVE RECTIFICATION.

These diagrams show by the dotted lines how the direct current fluctuates if not passed through a smoothing circuit: (a) half-wave, and (b) full-wave rectification.

Smoothing Networks

Although the current is always in the same direction on the condenser side of the rectifier circuits just referred to, the arrangements shown would be of little use as they stand, because the direct current consists of sharp pulses which fluctuate widely between a maximum and zero, while a steady direct current is required for the receiver. These current peaks, therefore, have to be smoothed out to produce a steady current.

The reservoir condenser connected across the D.C. side of the rectifier goes a long way towards reducing the fluctuations which will be much greater if this condenser is too small. As long as the alternating voltage of the transformer secondary is higher than the condenser voltage the condenser charges up, as shown by the rising portion of the incompletely smoothed voltage curve given in Fig. 5. Over the portion *bc* the condenser voltage is greater than the alternating voltage from the transformer and the condenser discharges into the load. It will be noted that with the same size condenser, the direct voltage fluctuates much more in a half-wave rectifier circuit than on a full-wave circuit, so that the former requires more smoothing than the latter to produce a steady direct current. In either case the fluctuation is still too great to be applied to the anode circuit of the receiver and, without further smoothing, would produce a loud noise in the loudspeaker which would drown all radio reception.

Further smoothing consists first of an iron-cored inductance or choke, the effect of which is to resist the change of magnetic flux through it and therefore to damp down any current variation. Finally, any residual current variations are smoothed out by a further condenser. The conventional smoothing circuit of a rectifier consists, therefore, of an iron-cored choke between two parallel connected condensers across the D.C. terminals

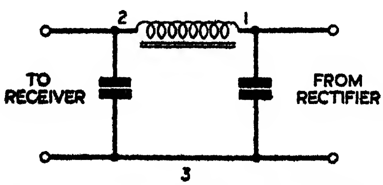


FIG. 6.—NORMAL TYPE OF SMOOTHING CIRCUIT FOR A RECTIFIER.

of the rectifier (Fig. 6). Condensers used in such smoothing circuits are often supplied in a block form in one unit with three terminals, terminal 3 (Fig. 7) being the common one. The block is generally labelled in terms of the capacity of the two condensers, *i.e.*, 4 mfd. + 4 mfd. and so on.

The degree of smoothing obtained with the reservoir condenser is increased by making this condenser larger so that it holds a correspondingly larger charge and its voltage does not fall so much over the portion *bc* of the curve of Fig. 5 (a). Increasing the condenser capacity too much, however, has another and undesirable effect. Since the condenser voltage, on partial discharge, falls less it will also charge during a shorter period and at a much higher rate owing to its larger capacity. The valve will thus be called upon to furnish a much higher "peak" current and this may impose sufficiently heavy a strain on it to shorten its life. Valve makers specify the most suitable value of the reservoir condenser to prevent possible overloading in this way. The condenser values are usually from 4 to 16 mfd.

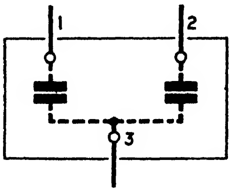


Fig. 7.—Condenser Block for Smoothing Circuit.

Choke and Condenser Ratings

For all normal receivers, a choke of about 32 henries is adequate. The requisite values of both components depend on the total direct current delivered. If this is very small they can be reduced in value without making the smoothing worse. For instance, in the case of the power supply to a cathode ray tube where the total current, say, is only about 1 milliampere, the reservoir and smoothing condensers can be reduced to, say, 0·5 mfd. and the smoothing inductance can be replaced by a plain resistance.

Both condensers should be of reputable make and labelled to indicate that they are suitable for standing up to the peak A.C. voltage, which is roughly 40 per cent. more than the R.M.S. or normally quoted value of the secondary of the mains transformer, because any breakdown of insulation in the condensers will not only result in failure to provide any direct current for the receiver set but will result in a complete or partial short circuit which will either irreparably damage the valve by serious

overload or burn out the transformer winding. In view of their smaller size, electrolytic condensers are generally used. The choke should also be rated to possess its specified inductance at the full load current the power pack is expected to provide. The core section must be large enough to prevent partial magnetic saturation, otherwise the inductance will be reduced when the full current passes through the coil resulting in less complete smoothing and the possibility of mains hum getting into the receiver. The resistance of the choke should be as low as possible because such resistance represents a loss in voltage between the rectifier valve and the receiver.

Very often the field winding of the loud speaker is used as part of the smoothing choke. This winding can be designed to have the necessary inductance to smooth the direct current to the set and at the same time provide a sufficient number of turns to furnish the necessary magnetic field for the loudspeaker magnet. As the current will usually be low, a large number of turns of wire will be needed for the latter purpose so that, owing to the limited space available, fine gauge wire will have to be used. Consequently, the field winding type of smoothing inductance will have a fairly high resistance and an appreciable voltage from the rectifier will be lost. Alternatively, the field winding may be connected across the positive and negative D.C. terminals where its high resistance and low current consumption would be an advantage rather than otherwise but, of course, the winding then plays no part in the smoothing, though it will stabilize the voltage by imposing a small load on the direct current supply. Where A.C. supply is available the voltage drop due to a series-connected choke can always be compensated for by providing a correspondingly higher transformer secondary voltage, but with A.C./D.C. sets, where no transformer is included and the H.T. voltage must be something less than that of the supply mains, the voltage would be still further reduced and could hardly be tolerated.

The Rectifier Valve

A desirable feature of the rectifier valve is that its impedance shall be as low as possible because the path between the cathode and anode inside the valve is really part of the direct current circuit and the voltage drop across it is subtracted from the voltage available for supplying the receiver. Consequently,

FIG. 8.—DIAGRAMMATIC REPRESENTATION OF A METAL RECTIFIER.

The direction of the arrow head indicates the direction in which current passes.

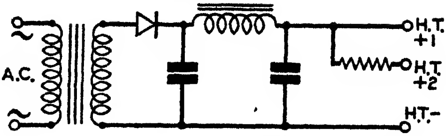


FIG. 9.—HALF-WAVE RECTIFIER.
Using metal rectifier and voltage dropping resistance in one D.C. supply lead.

if the valve has a high resistance, the voltage drop across it will vary much more than if its resistance were low, when the current demands of the set alter. This is usually expressed by saying that the circuit will have a poor voltage regulation. Such fluctuations in the direct voltage are very undesirable and worsen the reception of radio signals.

The lower the resistance of the valve and the secondary transformer voltage the better the regulation of the circuit. Reducing the spacing between the anode and cathode of the valve during its manufacture reduces the resistance of the internal path, but this cannot be carried beyond a certain point, otherwise there is a possibility of an arc passing between these electrodes when the voltage is reversed, i.e. when the anode is negative and when no current should therefore pass through the valve in this way causes it to become " soft " and destroys the rectifying action. The need for getting rid of the heat from the cathode must also be remembered. Too close spacing of the electrodes prevents heat dissipation.

Some rectifiers have directly heated cathodes, some indirectly heated. When the former are used, the amplifier valves which are nearly always indirectly heated do not reach their full emission till after the rectifier valve, consequently the rectifier valve is on load for some seconds and the open circuit voltage of the reservoir condenser is much higher than the normal working voltage. For this reason the condensers are subjected to a higher voltage and the risk of breakdown is rather higher than with

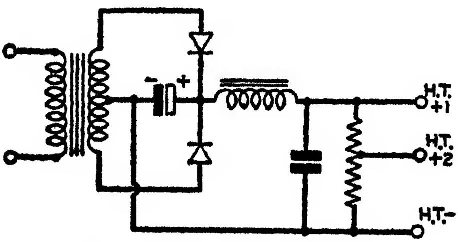


FIG. 10.—FULL-WAVE RECTIFIER.
Using metal rectifier and potentiometer tapping for voltage adjustment on one D.C. lead.

a directly heated rectifier valve. The cathode of an indirectly heated valve rectifier is usually connected to one side of the heater.

Metal Rectifiers

Another useful device for obtaining direct current from an alternating supply is the dry plate metal rectifier which has been referred to briefly in Chapter III. Units are available which can supply much greater current than a valve rectifier when required. The original metal rectifiers consisted of discs of copper coated on one side with a layer of cuprous oxide, the combination of metal and oxide having the property that current passes from one layer to the other more easily in one direction than the other when an alternating voltage is applied between them, so that it acts as a rectifier. By building up an assembly of a number of such circular discs and providing the sections with cooling fins to radiate the heat generated, full wave as well as half wave rectifiers can be produced. Practically any voltage and magnitude of direct current can be obtained by correct selection of the size and number of the discs. In some of the metal rectifiers now in use, selerium is used as one of the elements.

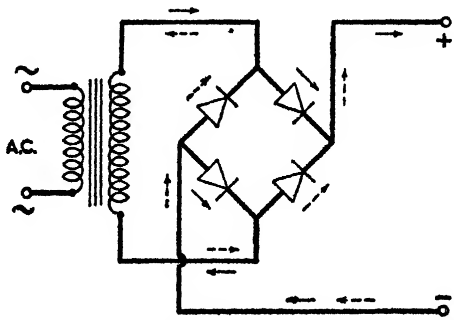


FIG. 11.—METAL RECTIFIERS CONNECTED IN A BRIDGE CIRCUIT (SMOOTHING CIRCUITS OMITTED).

This circuit does not need such a high secondary transformer voltage as that of Fig. 10.

Metal rectifiers are indicated on diagrams by the symbol shown in Fig. 8, the arrow head indicating the direction in which the current passes through the device. Metal rectifiers usually require a transformer between the alternating supply and the direct current load and like a valve rectifier need to be followed by a reservoir condenser and smoothing network if a steady direct current is required. In some cases, such as battery charging circuits, of course, this is not necessary. They also have an advantage over valve rectifiers that no filament heating

circuit is required. Besides the use of these units connected as full and halfwave rectifiers, shown in Figs. 9 and 10, another circuit known as a bridge connection employing four such rectifiers and illustrated in Fig. 11, is also widely used. The full and dotted arrows in Fig. 11 show the direction in which current passes during the two halves of the supply voltage. This circuit has the advantage that a lower voltage is required on the transformer secondary. Metal rectifiers are largely used for battery charging circuits.

Mains Transformers

Obviously it would be very uneconomical for the manufacturers of receivers to make a different set for each different supply voltage. Moreover for transportable, or demonstration apparatus it is essential to have a receiver which operates on any voltage likely to be encountered. Consequently, the transformers of A.C. mains sets are provided with tappings on the primary winding.

To reduce the number of tappings to a minimum and cut down the cost of production, the arrangement shown in Fig. 12 is usually adopted. This form of terminal connection enables any voltage in steps of 10, between 200 and 250, to be selected. For instance for a supply voltage of 220 connection should be made to terminals 2 and 5.

Winding Details

The windings of the mains transformer are expressed in RMS volts and in the case of centre tapped windings the voltage of each half is expressed. Thus 350 + 350 which indicates that in a full wave valve rectifier circuit 350 volts is applied to each anode. To identify the various windings of a mains transformer a colour code has been adopted which is adhered to by most makers. This is fully explained by the diagram of Fig. 13 and is a great help in tracing the wiring of a set, or identifying the windings of a transformer which has been disconnected or removed from a set.

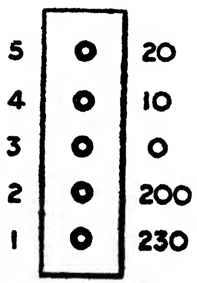


FIG. 12.—PRIMARY TAPPINGS FOR MAINS TRANSFORMER.

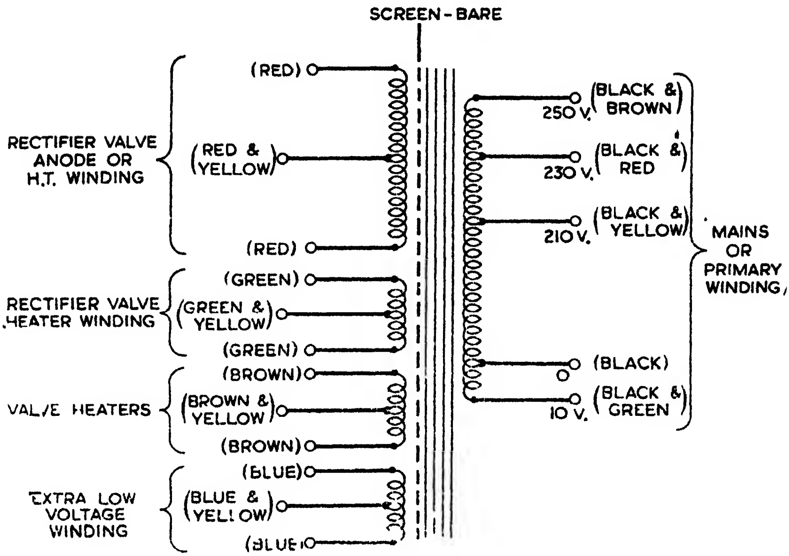


FIG 13.—COLOUR CODE USUALLY ADOPTED FOR IDENTIFYING THE WINDINGS OF A MAINS TRANSFORMER.

Cathode Heater Circuits

In a battery set, the cathode is directly heated by the current which passes through it from an accumulator. The early types of battery valves had filaments of 6 volts and some later ones of 4 volts rating, but all modern battery valves have 2 volt filaments to economise in battery space, since one cell only is then required. The filament of a battery valve is relatively thin and of high resistance to keep the current to as low a value as possible and reduce the drain on the accumulator. In mains operated sets, where ample electric power is available most valves are indirectly heated, though some output power valves have directly heated cathodes.

In A.C. sets, the heater is supplied by a winding on the mains transformer. The heater current is large compared with that of a battery valve and the heater wire is relatively thick so that it maintains a much more steady temperature during the fluctuations of the alternating voltage. The heat is communicated to the cathode by radiation and as the cathode is not, therefore, in direct contact with the heater, hum due to the mains voltage variation does not get into the valve circuit. Nevertheless

certain precautions have to be taken in the design of the heater-cathode system to prevent any possibility of mains noise getting into the receiver and spoiling the reception. Sometimes a metal screen is fitted round the end of the heater wire and connected to the cathode, and the lead to the grid is kept well spaced from the heater wires to prevent pick up of noise at the grid terminal of the valve. Directly heated valves where used are always in the output stage. They have cathodes with sufficient thermal inertia to enable them to be connected directly to a low voltage winding on the power transformer.

A.C./D.C. RECEIVERS

In the case of mains operated receivers intended to be used on D.C. supplies, modern practice is to include a rectifier valve so that the set can also be used on A.C. mains though it is at some disadvantage in the latter case compared with sets designed for use on A.C. only. Since it is practicable to construct robust heaters only for operation at relatively low voltages, the problem is how to secure the necessary low heater voltage from the D.C. mains. The most efficient and only method adopted in practice for D.C. mains is to connect the valve heaters all in series. For this purpose, the valves must all have the same current rating. In such receivers, the available H.T. voltage is always less than the supply mains voltage though this is, for small receivers at any rate, no great disadvantage since modern output valves are available for providing ample power at anode voltages of less than 200.

A typical arrangement of the power supply for an A.C./D.C. receiver is given in Fig. 14. It will be noted that the valve heater and the heaters of all the remaining valves together with the dial lamp—if any—are in series requiring that they shall all pass the same current and that, as the rectifier valve is in the H.T. supply lead, the voltage available for the amplifier is reduced by the drop across this valve and its attendant smoothing circuit. The rectification is half-wave only; it is not possible to introduce easily a full-wave rectifier into a circuit of this type. Connected to the mains terminal is a pair of high-frequency chokes and condensers which form a filter circuit the function of which is to prevent mains disturbances from entering the

set. Since the rectification is only halfwave, the choke and condenser in the smoothing circuit will need to be larger then those used in an A.C. set having a transformer-connected full-wave rectifier.

The voltage ratings of A.C./D.C. valves usually range from 6·3 volts to 26 volts though there are some with higher voltages. Valves have been constructed with the heaters operable at mains voltage, but this is not British practice. The total voltage of all the heaters including that of the rectifier and dial lamp added together will be less than the supply voltage and the difference must be made up by the inclusion of a suitable resistance in the same circuit. A barretter which is a resistance with special characteristics which will be referred to later is often employed for such a purpose. It will be noted that in the case of series connected heaters, since all the valve cathodes are connected directly or through a bias resistance to the chassis or earth, there will be a considerable difference in voltage between the heater and cathode of some of the valves and their insulation must be high enough to stand up to this.

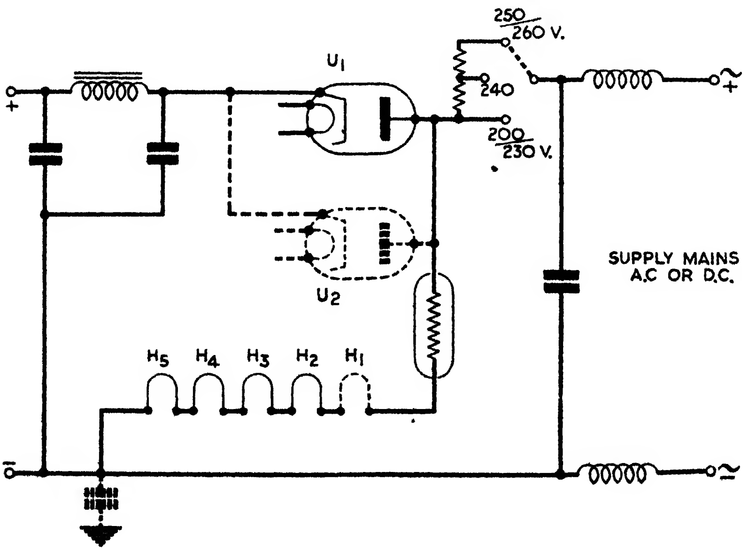


FIG. 14.—POWER SUPPLY FOR AC/DC TYPE OF SET.
Supply mains can be AC or DC.

Barretters

With A.C./D.C. sets where the valve heaters are all in series, there are two alternatives by means of which the set can be operated on more than one voltage. A tapped resistance may be included in the circuit, or a barretter may be used. Suppose for instance, we have a set with 5 valves including the rectifier valve each of 6·3 volt rating connected in series. This circuit will require a total of 5 × 6·3 or 31·5 volts. Suppose this is to be used on a 200 volt supply. Then 200 − 31·5 volts or 168·5 volts will have to be taken up by the resistance and since the current in the circuit is 0·3 amps., the value of the resistance will need to be 168·5/0·3 = 560 ohms and large enough to carry the current of 0·3 amps without overheating. Similarly, if the same set is to be used on a 250 volt supply, the voltage to be taken up by the resistance will be 250 − 31·5 volts or 218·5 volts and the total extra resistance then required will be 218·5/0·3 = 728 ohms. If the set is to be used on other voltages between 200 and 250 then the 728 ohm resistance will need to have further tappings at appropriate points.

Alternatively, a barretter may be used in place of the resistance. This consists of a glass bulb containing an iron wire filament, the bulb being filled with hydrogen. The wire is usually wound in a cage formation, something like the old type of vacuum filament lamp, though spiralized wire is also used. A barretter has the special property that over a certain range of voltage, depending on the particular type the current through the device is constant. Thus, for instance, the Osram 301 barretter has a range of 138 to 221 volts which means that for any voltage in this range, the filament of the barretter will pass a constant current of 0·3 amps and this current will not change if the voltage varies anywhere over this range. Now, in the example just quoted, we saw that the voltage to be absorbed varied from 168·5 to 218·5 volts for any supply between 200 and 250 volts and as this is within the range of 138 − 221 volts as applied to the Osram 301 barretter, such a barretter would be suitable to use in place of a resistance for absorbing the voltage difference between the mains and that required for the receiver. The example quoted is true whether the supply is A.C. or D.C. Although practically the same power is wasted in the barretter as in a tapped resistance, the barretter has the advantage that only two mains terminals are required for any voltage in this

range and the user is not bothered in altering the mains connections. Its disadvantage is that it is a replaceable component since the filament may fracture by burn out, or transit damage, whereas the resistance if correctly designed has an indefinite life.

ELIMINATORS

The term eliminator originated in the early days of wireless to indicate a means of obtaining the H.T. supply from D.C. mains in order to eliminate the H.T. battery of the receivers which were at first practically all battery operated. It really represented the first attempt to operate radio receivers from supply mains. Consequently, though the term could be applied to any piece of apparatus designed to cut out batteries and the trouble of their upkeep, it has been restricted by usage to the static form of H.T. power supply unit suitable for use with D.C. mains. It is the simplest form of mains power unit and is still often employed as a means of reducing the upkeep of the set where a user has a battery set and wishes to reduce battery maintenance.

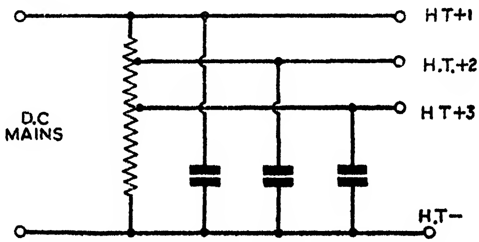


FIG. 15—D C MAINS H.T. ELIMINATOR.

Fig. 15 shows the simple arrangement of a D.C. mains eliminator for feeding the anode and screen grid circuits of a battery receiver. The voltage available cannot, of course, exceed that of the mains supply, but any lower voltage can be obtained by connecting a resistance across the mains and taking tappings at the appropriate points, each tapping point being connected to its own smoothing condenser. Thus, in Fig. 15, three values of H.T. voltage are made available H.T. 1 being the highest and used for the anode of the output value, H.T. 2 and H.T. 3 being lower voltages for the anode and screen grid voltages of the high-frequency or detector valves. In order to secure good regulation, i.e. small change of voltage due to variation of load, the current through the whole resistance across the mains must

be large compared with the current taken off at any one tapping. This, of course, is wasteful in power, but is not of any great disadvantage where mains supply is available.

VIBRATORS

A form of converter enabling high voltage, direct current to be obtained from accumulators and largely used for car radio is the vibrator. This is really a mechanically operated switch and uses the same principle as the buzzer, the ordinary electric bell and the make-and-break on a spark coil, with the addition that besides interrupting the battery circuit, the moving contact makes and breaks the current feed to the primary of a step-up transformer. These pulses of direct current induce high voltage A.C. in the secondary winding of the transformer and this high voltage current is rectified by a metal rectifier and subsequently smoothed, as shown in Fig. 16.

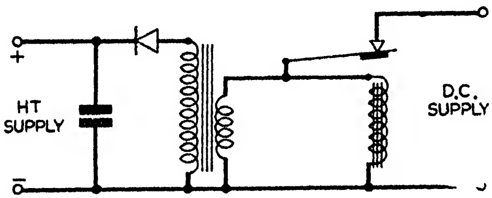


FIG 16—SIMPLE FORM OF VIBRATOR FOR OBTAINING H T. SUPPLY FROM A BATTERY.

Though the principle of the vibrator is very simple, great care has to be exercised in its design otherwise it will work badly, will take a heavy current from the battery and will probably burn the contacts severely, resulting in short life. To deliver maximum power for minimum current consumption, the rate of vibration, the timing of the make and break contacts and the transformer winding all have to be matched up, otherwise in addition, the insulation of the circuit may be damaged by high induced voltages. Generally, a condenser is connected across the transformer winding to form as nearly as possible a resonant circuit. By an elaboration of the simplest type of vibrator through the addition of extra contacts, the unit can be made self-rectifying so that the metal rectifier is no longer required. The principle of a vibrator of this type is shown in Fig. 17 where with three sets of contacts both windings of the transformer are disconnected from or in contact with the vibrator reed at the same instant. Vibrators are usually sources of radio-frequency disturbances and therefore, require efficient

suppressors fitted to them. They are very useful for small power output, but as the power is increased, there is greater difficulty in maintaining the contact surfaces and a rotary transformer is to be preferred for large receivers.

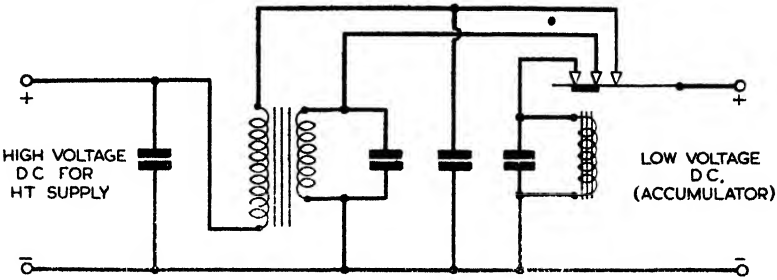


FIG. 17 —SELF-RECTIFYING TYPE OF VIBRATOR.
By means of extra contacts on the vibrator reed, the high-voltage alternating current is converted into direct current

ROTARY TRANSFORMERS

The rotary transformer consists of a combination of small motor and generator, and has an armature carrying two windings with a commutator at each end of the shaft, and a common field winding. In places where a low voltage lighting system or batteries only are available, it is the most convenient means of securing high voltage D.C. from a low voltage D.C. supply. By a suitable selection of the armature windings, the machine can be driven from any particular voltage supply to generate current at any other required voltage. Due to losses in conversion, the output in watts is always less than the input but efficiencies of 70 per cent. are easily obtained.

Modern rotary transformers are efficiently shielded and provided with interference suppressor circuits so that the generated current is perfectly steady when passed through a suitable smoothing circuit like those referred to in connection with valve rectifiers, and no interference due to the presence of the motor is experienced during reception. There is no hum or crackle in the loud speaker and the purity of reception is at least as good as on any mains-operated set.

For transportable public address equipment, which is nearly always carried on a motor-van, this type of machine is ideal since the car battery receives its charge during transit and the battery is then ready to furnish all the power needed for the

demonstration. Its light weight and small maintenance makes it far preferable to an accumulator battery, which for the same power output would be bulky and heavy.

These D.C.—D.C. generators find useful application in low power transmitters, where voltages up to 1,500 may be required. This is a type of supply which, in the absence of mains, would present some difficulty in producing. Thus, as H.T. generators for aircraft, yachts, lighthouses, etc., they are most useful.

Furthermore, rotary machines are also designed for D.C.–A.C. converters and these machines resemble somewhat the large rotary converters in frequent use in generating stations.

MOTOR GENERATORS

These small machines are elaborations of the rotary transformer principle. They are driven by a motor which may be designed to operate from A.C. or D.C. supply. The generator, which carries two windings, is connected to the motor by a flexible coupling so that separate supplies are made available, a low voltage source for the valve heaters and an H.T. supply for the anode circuits. This is the most satisfactory method of providing electrical supplies for high power receivers or transmitters where D.C. mains are available; even for A.C. mains the arrangement compares favourably with static rectifiers. The driving motor is usually an induction motor if the source is A.C. or a compound or shunt wound motor if D.C. In some machines the generator and motor have a common armature shaft with separate field windings with a third winding provided for the low voltage heater circuits. Some machines have permanent magnet fields. Hand or pedal-operated generators are sometimes employed for portable transmitters or for use in emergencies such as would occur in the forced landing of an aircraft, where the normal power supply might be put out of action. A double wound generator geared in about a 25 : 1 ratio, giving an output of about 40 watts, with a hand speed of 90–100 r.p.m., has been used for such purposes.

INTERFERENCE SUPPRESSION

Electrical machinery and many forms of domestic and industrial electrical appliances are potential generators of disturbances which, under certain circumstances, can interfere with the reception of radio receivers in the vicinity.

When a light is switched off in a room where a mains receiver is working, a click is heard in the loudspeaker, and if there is any apparatus nearby, such as a commutator motor, where electrical circuits are being repeatedly broken, a continuous noise may be heard in the receiver.

Interrupting electrical circuits may generate either high or low frequency disturbances and the latter may consist of continuous crackling, buzzing, or humming noises, some of which are characteristic of the source causing the trouble. Such disturbances are easily distinguished from atmospherics which are troublesome only in hot weather and vary from day to day with no regular sequence.

The removal of these electrical disturbances consists of providing, usually by means of condensers and inductances, paths of low impedance which divert the interfering impulses and prevent them from reaching the receiver. Resistances are also used for damping out high frequency disturbances.

Types of Electrical Interference

Interference may reach the receiver by one or more of the following ways (Fig. 18):

Direct radiation from the source.—This is, except in the case of high frequency electromedical apparatus, car ignition circuits on television frequencies, etc., usually the least troublesome since on broadcast bands, direct radiation only extends a very short distance. There may be cases where arcing at the collector from trolley-bus overhead wires or electric railways may cause radiated disturbances to receivers adjacent to the route.

Conducted interference—the most usual type of interference. Electrical disturbances originate at the source and travel along the wiring to the receiver, entering the set by the mains lead. The noise is usually of low frequency, though high-frequency components may also be present.

Mains-radiated interference.—Interference may reach the receiver by radiation from electric supply mains, telegraph wires, etc., near the set. It may travel a considerable distance from the source through the electrical wiring to be picked up finally by the aerial or wiring of the receiver.

Secondary radiation.—Metallic conductors not carrying current, i.e. from neighbouring aerials, water-pipes, etc., are sources of secondary radiation.

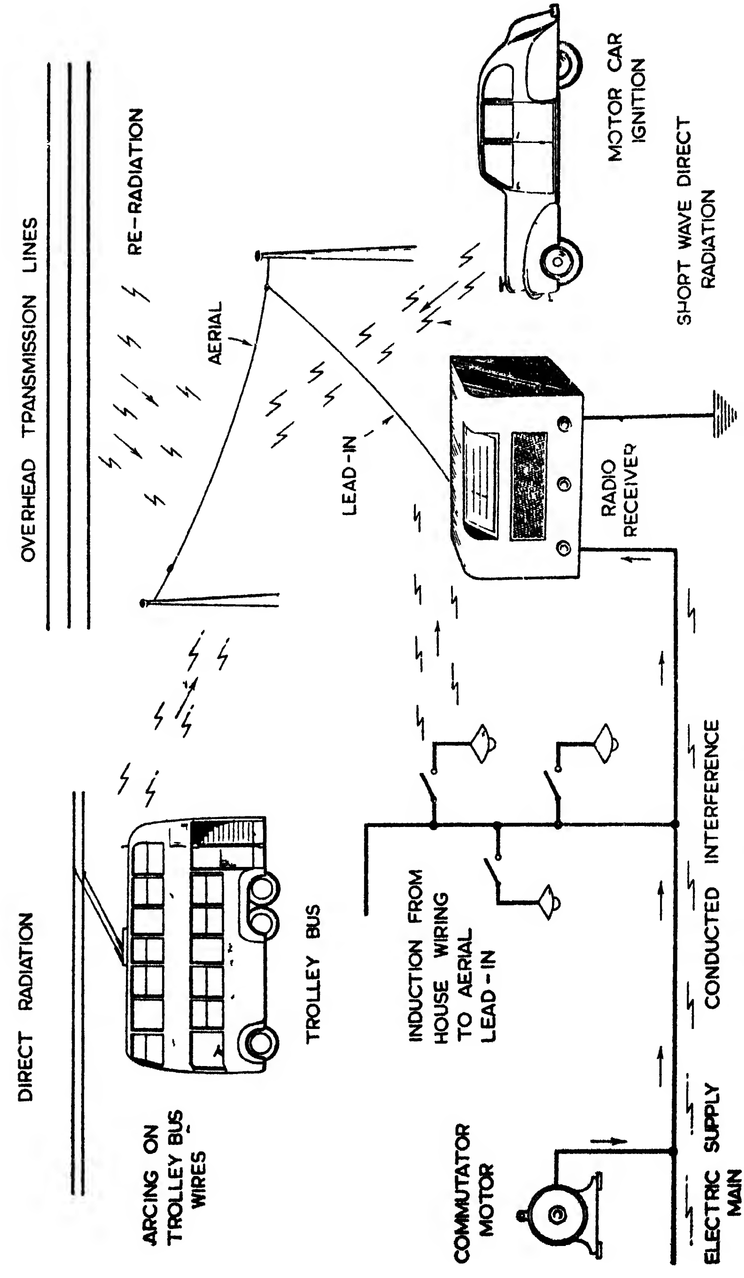


Fig. 18.—Types of Radio Interference due to Electrical Apparatus.

All four types of interference are possible with mains receivers, but battery sets, remote from supply mains, exclude mains-radiated or conducted disturbances. Directly radiated interference increases as the receiver wavelength decreases and if the disturbance is worse on long wavelengths, mains-conducted or re-radiated interference is probably present. Disconnection of the aerial will indicate whether the disturbance is being picked up in the aerial circuit or not.

Unwanted noise, assuming the set itself is in order, can, therefore, enter the circuit in three ways : (*a*) pick-up on the aerial or lead-in wire ; (*b*) injection into the set through the mains connection (mains operated sets only) ; (*c*) induced in the internal wiring by stray electric fields.

Identifying the Source

Often the source of interference will be obvious or easily traced from the characteristic nature of the disturbance. More troublesome causes may need the assistance of a battery set—known to be free from defects—with a frame aerial to trace the direction from which the disturbance is coming. Using such a receiver, the effect of cutting off the electric supply at the main switch should be noted. Bad cable joints and defective switches are often the cause of intermittent crackling. Unsheathed cables in wooden troughing can sometimes be troublesome in producing interference. It is necessary before attempting a cure to locate the source, identify the channel by which the disturbance reaches the receiver and find out on which wavebands the disturbance is worst.

Suppression at the Source

On the ground that "prevention is better than cure," interference should be suppressed at the source, though, in general, suppression at the receiver, as well as at the source, is necessary. Typical circuits which are included in proprietary types of suppressors are shown in Fig. 19, the simplest arrangement being that of Fig. 19 (*a*). An alternative arrangement is shown in Fig. 19 (*b*), which is used where one main at the station is earthed. There is usually an economic limit to the size of condensers used, above which increase in capacity will not remove the interference, though it may reduce it.

Where condenser paths prove incompletely effective, chokes are included in the line circuit to offer high impedance to the interference (Fig. 19 (*c*)). Since these chokes carry the line current, they must be of low resistance to avoid appreciable voltage drop. In most cases metal casing or screening at the source should be earthed. Resistances are used as suppressors of high-frequency oscillations in the plug-heads of internal combustion engines.

Suppression circuits generally used for particular cases are :

Commutator Motors.—Type shown in Fig. 19 (*a*). A high frequency choke should be included in the earth lead if the performance is better without the earth connection.

A.C. Synchronous and Induction Motors.—These machines do not usually generate interference.

A.C. Repulsion Motors.—The condenser unit should be connected across the mains feed to the motor and not across the brushes.

Small Unearthed Motors in Portable Appliances.—The centre point of the condenser filter is taken to the motor frame. This makes the frame above earth potential and the possibility of shock is avoided by keeping the condensers small (Fig. 19 (*d*)).

Electric Signs—Flashing Type.—Small condensers are connected across the contacts in series with resistances to form

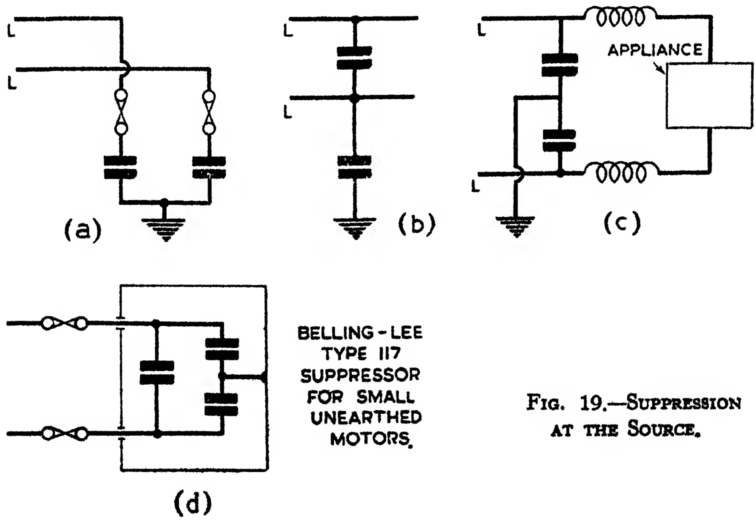


FIG. 19.—SUPPRESSION AT THE SOURCE.

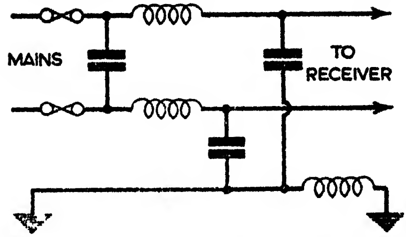


FIG. 20.—SUPPRESSION AT THE RECEIVER. Typical All-Wave Set Mains Suppressor. (*Belling-Lee*).

heavily damped circuits to avoid resonance effects. High-frequency chokes may be included in the mains supply leads.

Electric Signs—Discharge type.—Condenser filters are included across the transformer primary with a low-frequency choke in the H.T. circuit, preferably near the centre of the sign with its case earthed. H.T. wiring is in screened earthed metal casing and an open metal shield included between the transformer primary and secondary.

X-Ray and Ultra-Violet Ray Apparatus.—Direct radiation on short waves and mains conducted disturbances over large distances are produced. Complete suppression sometimes requires operation in a screened room. Choke filters on all wiring passing out of the operating room are necessary, and sometimes special suppressors are required.

Trolley Buses.—Condenser suppressors, with earthed centre points at fixed distances along the route and high-frequency chokes in the main and controller circuits are usually fitted.

Lifts.—The makers of equipment usually supply the necessary suppressors for preventing interference from the motor, control panel or trailing cables.

Motor Cars.—Resistance suppressors are included in the sparking-plug leads to prevent high-frequency radiation which is troublesome to television receivers in the vicinity. Lower frequency disturbances which may be troublesome to a receiver on the car itself originate at the contact breaker, the distributor, petrol pump, battery-charging system and wind-screen wiper, all of which may require the use of screened cable and condenser suppressors.

Suppression at the Receiver End

This form of suppression may be required where it is not possible to suppress at the source, or even in addition to it. It involves either or both (*a*) condenser filter circuits at the mains input to the set, or where the mains enter the premises (Fig. 20 or Fig. 21) the use of a special screened aerial to cut

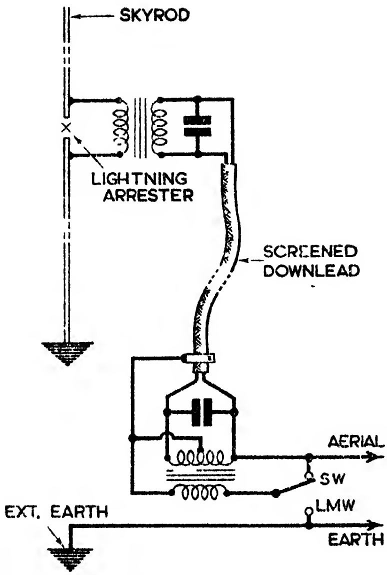


FIG. 21.—CIRCUIT OF BELLING-LEE SKYROD AERIAL SYSTEM. (*Belling-Lee*)

out radiation pick-up. It must, of course, be noted that a mains input filter will not remove mains hum, which, if present in the receiver, indicates that the rectifier circuit is defective.

Special Aerial Systems

Electrostatic or electromagnetic pick-up on the aerial can be reduced by the use of a special system, designed to increase the signal to noise ratio, without introducing excessive signal loss through added capacitance which would result from the use of a simple shielded lead-in.

Most anti-interference aerials involve the principles adopted in transmission line practice. A voltage step-down matched transformer (Fig. 21) couples the aerial to the lead-in. The voltages of the currents passing down the lead-in wire are thus reduced so that the capacitance effect of the screening is counteracted.

At the receiver end of the screened down lead the signal voltage is again stepped up by a further matching transformer. In the case of the type of aerial illustrated, losses are further reduced by tuning the transformer windings so that a resonance effect is produced over the wavebands covered.

Choice of site in installing the aerial is important, and its height and location must be in the region of minimum interference, since disturbance which finds its way into the aerial terminals of the set cannot subsequently be eliminated.

CHAPTER XIX

ACCUMULATORS

THE basic advantage of the secondary cell, also known as the storage cell or accumulator, make it suitable for a wide range of practical applications. A familiar example is its use in motor-cars as a source of ignition and lighting, and there is still an appreciable sphere of use for operating radio sets in places where no electric mains are available.

There are two different types of secondary cells or accumulators, known respectively as the lead-acid cell and the alkaline cell. The latter type is made in two forms ; one using nickel and iron, and the other nickel and cadmium for the respective sets of plates. Either form is much less subject to damage by mishandling than the lead-acid type, and during recent years the alkaline cell has found a widely increasing sphere of use.

LEAD-ACID CELLS

Various types of construction have been used by different manufacturers, but the broad principles are the same for all cells of this class. Two independent sets of plates, interleaved but not touching each other, are immersed in sulphuric acid and enclosed in a suitable container. Connections from the respective sets of plates are brought out to two terminals. A typical set of plates is shown in Fig. 1. With the exception of the active material, the construction is of lead or lead-antimony. Separators of wood or other material suitable to withstand immersion in acid are inserted between adjacent plates to prevent accidental short-circuit. The method of assembling the plates in the container is shown in Fig. 2.

Types of Construction

A most important part of the technique of manufacture is in the method of applying the active material to the plates. There are two forms of construction, known as the Faure (or

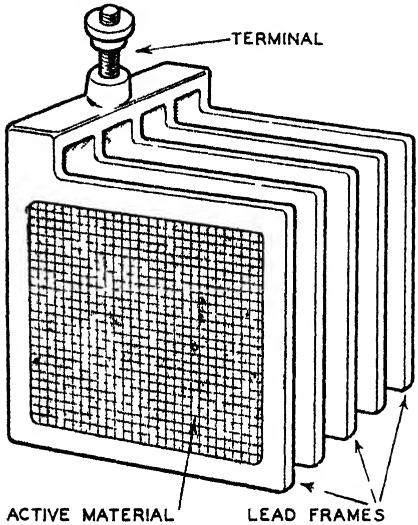


FIG 1.—ONE SET OF PLATES FOR LEAD ACID CELL

pasted) and the Planté (or formed), and modern constructions are based on one or other of these types.

Faure plates consist of cast lead-alloy grids with openings into which the active material is inserted in the form of a paste. Planté plates make use of a lead base on which the active material is deposited by a special forming process. There are several variants of each type of construction.

The active materials employed in lead-acid cells are lead peroxide for the positive plates and spongy lead for the negative. The sulphuric acid used for the electrolyte must be of the proper strength or concentration, as recommended by the manufacturers, and this will depend upon the use for which the cells are intended. The strength is measured by the specific gravity of the acid, which is the ratio of the weight of a given volume of acid to the weight of the same volume of pure water at a given temperature. The value ranges from about 1·205 to 1·215 for general purpose stationary cells to 1·25 for the cells used in car starter accumulators and as much as 1·28 for the batteries of electric vehicles. Unduly strong or weak solutions are harmful to the cells, and the manufacturers recommendations should always be followed.

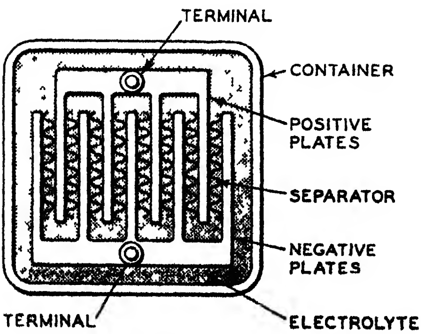


FIG. 2.—METHOD OF ASSEMBLING PLATES IN LEAD-ACID CELL.

The specific gravity of the acid is conveniently measured by means of a hydrometer, which virtually consists of a weighted

float, usually of glass, with a stem which is upright when the hydrometer floats in a liquid. As the level at which the hydrometer floats varies with the density of the fluid, being lower when the density is less, the stem is calibrated so that the density can be read directly on a scale at the point corresponding to the surface of the liquid, as shown in Fig. 3.

Forming and Charging Processes

In the case of a Faure construction with pasted plates, a red lead paste is used for the positive plates and lead monoxide or litharge for the negative. These materials are turned into the required form by the process known as forming, which is carried out by passing a suitable direct current through the cell. The chemical interactions caused in this way convert the red lead to lead peroxide and the litharge (lead monoxide) to spongy lead. These changes come about owing to the movement of ions, which, it will be recalled, are atoms or molecules of a substance with either a positive charge due to the loss of electrons, or a negative charge due to having acquired more electrons than the normal number corresponding to the uncharged or neutral atom.

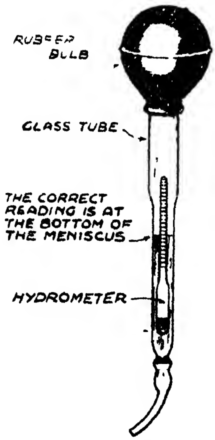


FIG. 3.—THE SYRINGE TYPE HYDROMETER.

In the process of forming, sulphur ions carrying a negative charge move to the positive plate where they give up their charge, and hydrogen ions carrying a positive charge behave similarly with respect to the negative plate. The combination of hydrogen (H_2) with the lead monoxide (PbO) of the negative plate results in the formation of lead (Pb), in a finely divided state known as spongy lead, and water (H_2O). The sulphur ions combine with the water, forming sulphuric acid (H_2SO_4) and freeing oxygen (O_2) which combines with the red lead (Pb_3O_4) of the positive plate to produce lead peroxide (PbO_2). The cell is now in its normal charged state, as follows:

Positive Plates :—lead peroxide (PbO_2).
Negative Plates :—spongy lead (Pb).
Electrolyte :—sulphuric acid (H_2SO_4).

The connection of a circuit to the terminals will now result in the flow of current through this circuit and the cell itself. It should be noted that according to convention, the flow through the cell will be from the negative to the positive plate, whereas during the forming or initial charging process just described, the current through the cell is in the opposite direction. During discharge through an external circuit, hydrogen is liberated from the positive plate and combines with the lead peroxide (PbO_2) of this plate and the sulphuric acid to give lead sulphate ($PbSO_4$) and water (H_2O). This production of water causes a lowering of the concentration and specific gravity of the sulphuric acid, and as the effect increases during continuance of the chemical

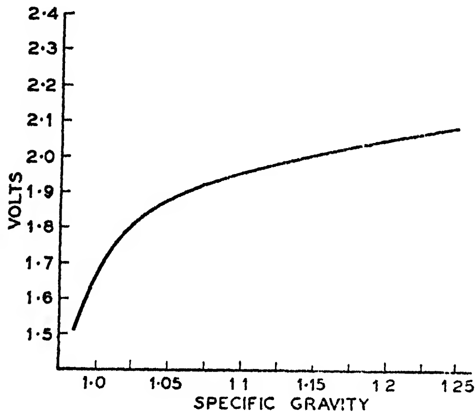


FIG. 4.—CURVE ILLUSTRATING THE RELATION BETWEEN VOLTAGE AND SPECIFIC GRAVITY OF ACID IN LEAD-ACID CELL DURING CHARGING.

processes, the specific gravity of the acid, as measured by a hydrometer, can be used as an indication of the state of discharge of the cell. Sulphur ions combine with the lead of the negative plate, producing lead sulphate at this plate also. If this process continues long enough, the cell becomes inoperative and is then in the discharged state, as follows :

Positive Plates :—lead sulphate ($PbSO_4$).
Negative Plates :—lead sulphate ($PbSO_4$).
Electrolyte :—water (H_2O).

The cell may be restored to its original charged condition by passing a current through it in the opposite direction to the discharge current, and consideration will show that this will be the case if the positive terminal of the cell is connected to the positive

terminal of the supply during the charging process. The passage of current through the cell from the positive to the negative plate in this way results in the oxidation of the sulphated positive plate, producing sulphuric acid, which raises the specific gravity of the electrolyte, and reduces the plate to lead peroxide (PbO_2) once more. At the negative plate, the combination of lead sulphate and hydrogen produces sulphuric acid and reduces the plate to spongy lead again. As the process continues, the specific gravity of the acid rises and the voltage of the cell increases, the relationship being approximately as shown by the curve in Fig. 4. The voltage of the cell and the specific gravity of the electrolyte give a combined indication of the state of charge of the cell. When

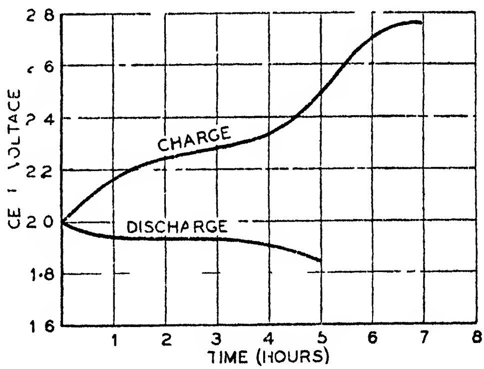


FIG. 5.—CURVES ILLUSTRATING THE VARIATION OF VOLTAGE WITH TIME DURING CHARGE AND DISCHARGE OF LEAD-ACID CELL.

the state of full charge is approached the cell also starts " gassing " owing to the liberation of hydrogen and oxygen, and this is a further indication that the charging process is nearly complete. In this state, the cell is in the same condition as it was at the conclusion of the forming process :

Positive Plates :—lead peroxide (PbO_2).
Negative Plates :—spongy lead (Pb).
Electrolyte :—sulphuric acid (H_2SO_4).

The curves in Fig. 5 show the manner in which the cell voltage varies with time during charge and discharge. The precise shape of these curves and the voltage values for given times will, of course, depend upon the type and condition of the cell and the circuits used, but for all lead-acid cells the charge and discharge curves are of the same general form. When fully

charged, the voltage of each cell is from 2·5 to 2·7 volts, falling to about 2·2. volts when the charging current is switched off. The positive plates assume a deep chocolate brown colour and the negative plates are a slate grey.

ALKALINE CELLS

This type of cell differs radically in construction from the lead-acid type and does not employ acid. The electrolyte is a solution of caustic potash or potassium hydroxide in distilled water, the specific gravity being about 1·19. In the nickel-cadmium cell, the active material of the positive plates is a nickel hydrate mixture which also contains graphite and other materials. For the negative plates, a mixture of cadmium and iron oxides is used. In the nickel-iron cell, the positive plates are of similar construction and iron oxides are used for the negative plates.

The chemical reactions in either form of cell are very complicated, but may be described in simple terms as the oxidation of the positive plates during charge and the reversal of this process, i.e. oxidation of the negative plates, during discharge.

Alkaline cells are much lighter for a given output than lead cells, owing to the lighter plate materials, and for this reason have been applied extensively to electric vehicles of various kinds. The nominal voltage per cell is about 1·2 volts, so that more cells are required for a given voltage than in the case of lead cells, e.g. five for a 6-volt battery as compared with three lead cells.

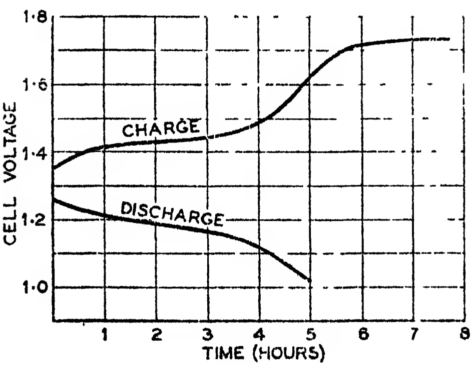


Fig. 6.—Variation of Voltage with Time during Charge and Discharge of Alkaline Cell.

The specific gravity of the electrolyte remains constant during operation, and voltage readings are used for finding the state of charge. The cell may be regarded as requiring recharge when its voltage falls to 1·1 volts. On charge the voltage will rise to the region of 1·7 volts, as shown by the curves in Fig. 6, which should be

compared with those for the lead cell (Fig. 5).

Alkaline cells may be discharged at rates up to the short-circuit value without damage, and in many ways are remarkably resistant to the effects of carcless use. In particular, they are not harmed by long periods of inactivity. The construction of a typical nickel-iron cell is shown in Fig. 7 and is seen to be rather more complicated than the normal lead cell. Notable features are the steel container lined with insulating material and the filler cap valve which allows the escape of gases from inside the cell but prevents the entry of air and consequent absorption of carbon dioxide which would have harmful effects.

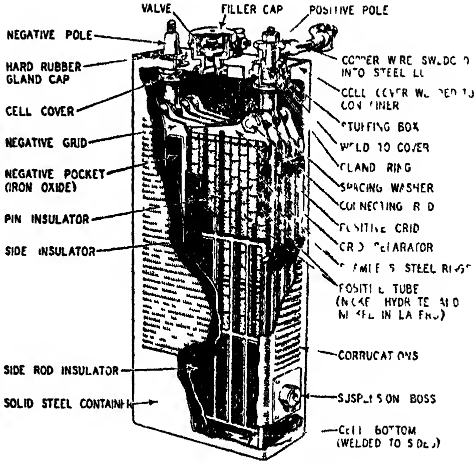


FIG. 7.—SECTIONAL VIEW OF ALKALINE (NICKEL-IRON) CELL.

THE CARE AND MAINTENANCE OF ACCUMULATORS

Lead acid accumulators are normally used with radio equipment and this section deals mainly with the care and maintenance of this particular type, but a short note on the precautions to be taken with alkaline cells has been included.

If a lead-acid secondary cell or accumulator is properly looked after and its working conditions are satisfactory, it will give no trouble during its working life. Accumulators which are used with radio apparatus are often neglected, especially those used for H.T. supply, and consequently their life is shortened and their ampere hour capacity is reduced.

The accumulator is usually despatched by the manufacturers without acid, and before it can be placed into service, acid of the correct specific gravity must be added and the accumulator given its initial charge. Various methods of giving the initial charge are recommended by the battery makers, and their directions given should be faithfully carried out.

The Electrolyte

The electrolyte is a solution of pure brimstone sulphuric acid and distilled water made to a specific gravity of 1·2 to 1·25. The purity of the acid and the water is essential to the efficient working of the cell. The common impurities of commercial sulphuric acid are, copper, iron, arsenic, and nitrous compounds, and each of these attack the active material and the lead frames of the battery plates very strongly and soon cause their destruction.

When making up the solution *always* add acid to water, as great heat is developed during the mixing process. The specific gravity of the solution is tested when cool and should be the exact figure given on the direction label on the accumulator. The electrolyte is then poured into the accumulator and should completely cover the plates. The plates will absorb some of the solution, and it will be necessary to add more to maintain the level. On no account should the top of the plates be allowed to become dry.

The Initial Charge

If one of the charging mains is earthed, it is best to connect the accumulator on to it. A test-lamp of the mains voltage is connected between each main and earth, alternatively, as shown in Fig. 8. The main on which the lamp does not light is the earthed one.

The charging current is adjusted to the correct value, making sure the positive pole of the supply is connected to the positive pole of the accumulator. The correct polarity may be ascertained by testing the supply terminals with pole-finding paper, the negative testing wire will give a stain on the paper. An alternative method of checking the polarity of the mains is illustrated in Fig. 9 In this instance the ends of the charging wires are dipped into a glass vessel containing water to which a teaspoonful of acid has been added.

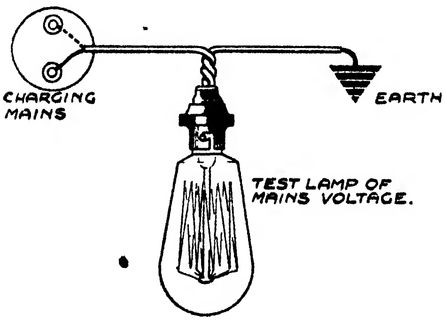


Fig. 8.—Finding the Earthed Side of the Battery Charging Mains.

Bubbles of gas will be liberated from around the negative wire. A test-lamp of mains voltage should be connected in series with the circuit to prevent a short-circuit. The initial charge should continue uninterrupted for the full period stated, when the accumulator should be gassing freely. The voltage should be 2·6 when the charging current is passing. The voltage test when taken with the accumulator on open circuit is of little value.

The colôur of the positive plates will be a deep chocolate and the colour of the negatives a blue grey when the accumulator is charged. The specific gravity of the electrolyte will have increased by about 0·5 per cent. during the charging process. Some battery makers recommend that the electrolyte be poured away after the initial charge and immediately refilled with new solution of the correct specific gravity. The accumulator is now ready for service.

Discharge

When the voltage of the accumulator has fallen to 1·8, the discharge should be stopped and immediately afterwards the re-charge should be commenced.

During the discharge of an accumulator, the chemical activity of the plates is gradually reduced and the specific gravity of the electrolyte falls. The plates now become covered with a film of lead sulphate which will be difficult to remove by the next charge if the discharge is taken too far, and the ampere hour capacity of the accumulator will be permanently reduced. These remarks should be borne in mind with H.T. accumulators which are very often left in a discharged state and owing to the small amount of electrolyte in this type of accumulator,

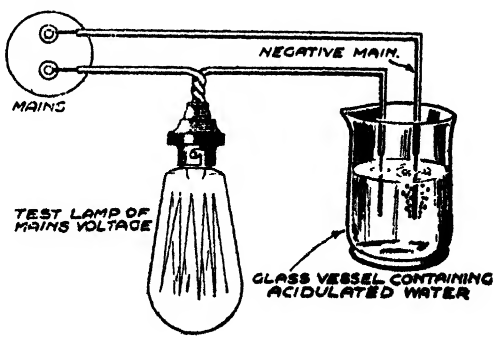


FIG. 9.—FINDING THE POLARITY OF THE CHARGING MAINS.

Bubbles of gas will be seen liberated from the solution round the negative main.

the electrolyte soon disappears, due to its chemical action on the plates and evaporation of the water in the electrolyte, causing the interior of the cells to be completely choked with lead sulphate.

Effect of Temperature

The maximum temperature at which an accumulator will work satisfactorily is 80°F. At higher temperatures the wear on the plates is excessive and their life will be considerably reduced. Working an accumulator at low temperatures reduces its capacity, but beyond this no harm will be done.

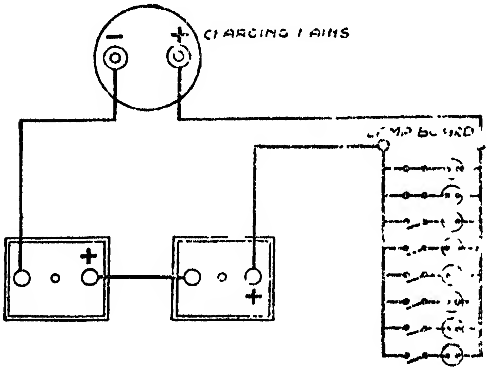


FIG. 10.—CONNECTIONS FOR CHARGING ACCUMULATORS WHEN THE NEGATIVE SIDE OF THE CHARGING MAINS IS EARTHED.

Accumulator Troubles

The most frequent causes of accumulators giving trouble and the effects resulting from these causes are :—

1. *Want of attention and Failure to carry out the Maker's Instructions.*—The effect of this neglect will cause unsatisfactory working of the accumulator, weak cells will not be detected when they first occur, and in time the plates of these cells will be ruined.

2. *Excessive Overcharging.*—This produces positive active material in excess, leading to an abnormal deposit of sediment, which in time will build up from the bottom of the accumulator container and short-circuit the plates. This incurs waste in using unnecessary charging current, and dissipates the electrolyte in the form of a spray which is lost if there is an opening in the top of the cell, and a falling off in specific gravity occurs when water is added to make up the deficiency. It also forms spongy

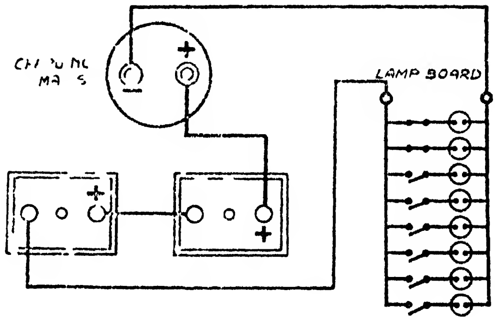
lead on the negatives, leading to treeing across the plates and producing weak cells.

3. *Running the Battery too Low on Discharge.*—The positive plates sulphate dangerously, the source from which buckling may arise. Makes the active material of the negative plates contract and so permanently lose capacity.

4. *Under-charging.*—The electrolyte gradually decreases in specific gravity, and the plates sulphate, which, if neglected it will be impossible to reduce.

5. *Using Impure Acid or Unsuitable Water for Topping up.*—The impurities will attack the plates, leading to their disintegration,

FIG. 11.—CONNECTIONS FOR CHARGING ACCUMULATORS WHEN THE POSITIVE SIDE OF THE CHARGING MAINS IS EARTHED



or the impurities will combine with the electrolyte, producing a precipitate and cause the specific gravity of the electrolyte to be lowered. The precipitate will fill up the space below the plates which is ordinarily required for normal deposit of sediment, thereby causing more frequent cleaning out than would be otherwise necessary.

Servicing

Topping up the Accumulator.—This is restoring the level of the electrolyte to the correct height with distilled water. The water obtained from rain-water cisterns, engine drains, peaty soil, and from hard water mains supply should not be used. Electrolyte should never be used to restore the level unless some has been spilled out of the accumulator.

A little vaseline smeared on the terminals will prevent any tendency to corrosion.

Removal of Sediment from Accumulator Boxes.—Carefully pour out the electrolyte into a suitable container and remove

the cover of the accumulator box. If the cover is made of bitumen it may be softened by passing steam from a kettle into the box. If made of celluloid, the joint between the cover and the sides is broken by inserting a thin-bladed knife. The cover and the plates are removed carefully to prevent the plates shorting with each other.

The box is now flushed out with clean water and dried, and the separators from between the accumulator plates taken out and cleaned. The separators are replaced and the plates and cover are fixed again in the box. The joint between the box and cover is remade. A bitumen joint is made by softening the bitumen again and kneading it to the sides of the box; a celluloid joint is made by running into the joint a solution of amyl acetate, acetone, and small pieces of celluloid which has been made to the consistency of syrup. Whilst the cover is removed, examine the terminal connections of the plates, and the condition of the insulating rubber bushes. These should be renewed if found to be faulty.

The electrolyte should be filtered and its specific gravity tested for correct strength before replacing it in the accumulator. The accumulator is now put on charge until it is gassing freely.

Treatment of Swollen and Buckled Plates.—Prepare pieces of wood, half inch longer and half inch wider than the plates. The number required will be two more than the number of separators used in the accumulator, and their thickness equal to that of a separator. The prepared wood should be planed and perfectly flat. Pour off the electrolyte from the accumulator box and remove the plates. The separators are taken out from between the plates, and a prepared piece of wood placed between adjacent plates. A piece is also placed over the outside face of the first and one on the outside face of the last plate. The whole of the plates are now sandwiched between the prepared pieces of wood, as shown in Fig. 12.

The composite block of plates and wood is now placed on a flat surface and a heavy weight put on the upper piece of wood and left there for two or three hours. Great care should be taken not to dislodge the active material on the surface of the plates when removing the separators and inserting the prepared pieces of wood between the plates.

Remove the weight from the upper piece of wood and replace the pieces of wood between the plates with the separators. The

plates and cover are fixed in position in the accumulator box, the electrolyte poured into the box, and the accumulator charged up until it is gassing freely.

Putting an Accumulator out of Commission.—Fully charge and then discharge the accumulator at the normal rate until the voltage of each cell has fallen to 1·84. The electrolyte is then poured out and replaced with pure water. Recommence the discharge, gradually reducing the resistance of the circuit until the accumulator voltage has fallen to zero. Now short-circuit the terminals of the accumulator and leave it for twenty-four hours. Pour off the water and the plates will now take no harm for an indefinite period. The wooden separators should be removed before finally storing the plates and immersed in water until required again.

Putting the Accumulator into Commission again.—Replace the separators between the plates and fit the plates and cover to the container. Prepare new electrolyte to the correct specific gravity and fill up the container with it to the working level. The charge should now be started at the normal rate and continued without interruption until the accumulator is fully charged. This charge will take the same time as an initial charge.

Jelly Acid Accumulators

The electrolyte in this type of accumulator is made in jelly form and should be kept thoroughly moist by the addition of a little distilled water before the commencement of each charge.

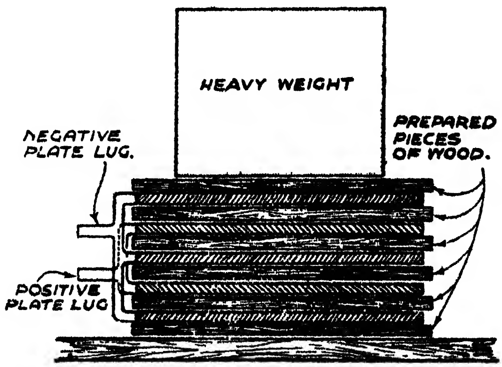


FIG. 12.—HOW TO TREAT SWOLLEN AND BUCKLED ACCUMULATOR PLATES.

A heavy weight is left placed on the assembly and left in position for at least two or three hours.

The electrolyte should be completely renewed every twelve months, and is done when the cells are in a fully charged condition. Attention to this will prevent "frothing," which often occurs with celluloid box accumulators after several months' use.

ALKALINE ACCUMULATORS

This type of cell is very sturdy and will stand high rates of discharge without buckling the plates. In order to preserve the plates, the specific gravity of the electrolyte, a solution of potassium hydroxide (KOH) in distilled water, must be kept within the limits of 1·19 to 1·16, but it should be borne in mind that, unlike the lead acid type, the specific gravity readings give no indication whatever of the state of charge. The electrolyte should be completely renewed after about two years, when working under normal conditons, as it absorbs impurities from the atmosphere. Distilled water should always be used for topping up the cells when evaporation has taken place. Electrolyte should only be used for this purpose to replace accidental spillage. Care must also be taken to prevent any contact with sulphuric acid, which will completely ruin the accumulator and it is advisable to ensure that no utensils which have been used in connection with lead acid accumulators are permitted anywhere near.

Charging

Owing to the difference in characteristics, alkaline accumulators should never be put on charge in circuit with the lead acid type, as this would be detrimental to both types.

The initial voltage is about 1·4 per cell when a discharged alkaline cell is put on charge at the normal rate (i.e. the 6 hour rate of charge), rising during the first half-hour to about 1·5 volts and then more gradually until after three hours another rapid rise takes place, so that at the end of the fifth hour the top voltage of about 1·75 to 1·8 is reached. The charge must then be carried on at the full rate for a further hour.

the primary and secondary windings being damped by resistances R 44, R 50, R 51, etc., The grids of the first three valves are controlled by a variable resistance R 47 in the cathode circuit, giving control of the I.F. gain and contrast of the picture.

The amplified I.F. signals pass to the full-wave balanced demodulator V 13 and V 14, R 73 and R 74 being the load resistances and the resultant signals enter the control grid of the vision frequency amplifier valve V 15. The small inductance L 43 in series with the anode load R 78 compensates for attenuation of the higher modulation frequencies. Thence, the signals are applied to the modulator electrode of the cathode-ray tube in order to maintain the D.C. component of the transmitted wave form, by which the comparative brightness of the picture is controlled.

These signals which contain the synchronising signals as well as the picture modulation are passed through R 89 to the grid of valve V 16 which separates the two by a process of amplitude discrimination. The line synchronising impulses are fed through C 91 and R 90 to the line time base, and the frame signals pass to the frame time base through the coupling transformer and filter R 80, C 62 and R 101 which remove the line impulses.

Time Bases

Relaxation oscillators, including argon gasfilled relays, provide the line and frame scans. This particular type of oscillator is capable of producing oscillations having a build-up which is relatively slow for part of the cycle, followed by a much more rapid return to the starting point. For the line scan, the charging circuit comprises R 92, R 93, R 94 and C 72 ; while R 99, R 100, R 102 and C 76 is the corresponding frame charging circuit. R 96 and R 104 control the frequency and R 92 and R 99, the amplitude of the line and frame time bases, respectively. The signals are then fed through C 73 and C 75 to the two amplifying valves, triode connected KT 66's. The line amplifier is coupled through a series fed split secondary transformer to the deflector plates of the cathode-ray tube, R 120 and R 121 damping the secondary to maintain linearily. R 105 and R 98 form the anode load of the frame time base amplifier which is parallel fed to the primary of the scan coupling transformer, R 98 providing control of linearity.

Power Supply

This follows the conventional design for valve rectifier circuits. Full wave rectification is provided for the "A" chassis by V 6 and for the "B" chassis by V 21. Independent smoothing filters are provided for the two time bases and vision receiver. The H.T. supply for the cathode-ray tube is furnished from a half-wave rectifier, the output of which is smoothed by R 118 and C 84. The necessary potential for the electrodes of the cathode-ray tube are obtained from the potential divider consisting of R110, R 111, R 112, R 113 and R 116. R 113 varies the potential to anode 2 and acts as a focusing adjustment, while R 110 and R 111 serve as picture centring controls in the horizontal and vertical directions. The overall brightness of the picture is adjustable by varying the cathode potential of the tube by R 115.

CHAPTER XXI

SHORT WAVE AND ULTRA SHORT WAVE TECHNIQUES

If we were to ask a radio engineer to discuss " Short " waves and " Ultra Short " waves, he would probably say, in the words now rendered famous by Dr. Joad, " It depends on exactly what you mean by ' Short ' and ' Ultra Short '." So we will begin by looking into what the terms mean and how they come to have their present interpretation.

As we have already learnt in the earlier chapters of this book, radio waves are electromagnetic waves, and the only way in which they differ from other forms of waves is in the wavelength.

The longest radio waves we have so far been able to generate are about 30,000 metres in length, that is to say, close on 20 miles. The short waves of a few years ago were round about 200/400 metres in length, or roughly about $\frac{1}{4}$ mile. These waves are then still quite long compared with the wavelength of light, which is somewhere of the order of $\frac{6}{1000000}$ ths of a centimetre.

Wavelengths

One of the main conclusions about the electromagnetic theory is that the length of the wave with which we are dealing multiplied by the number of its vibrations per second is equal to the velocity with which it travels through space. This may be expressed for those who like having things written in a mathematical form by the formula $V = n\lambda$ where V is the velocity, n is the number of oscillations or cycles or vibrations per second, and λ is the length of the wave.

All those who wish to understand the science of radio telegraphy, or indeed practically any branch of modern science, be it optics, heating, or even chemistry, should know this formula

and appreciate its implications. Let us, therefore, think for a moment what this formula means. First of all it is apparent that we have three factors which are related to one another, expressed by the three symbols in the formula. We have already stated that the wavelength may be long, as much as 20 miles, or it may be $\frac{1}{4}$ mile, or too short to measure with the most finely graduated ruler, as in the case of the wavelength of light.

Velocity of Waves

It has also been stated in Chapter V that the number of oscillations per second may vary, but so far as the passage of waves through empty space is concerned, the velocity or speed, V, is a fixed quantity, viz. 300×10^6 metres per second. It therefore follows from the formula, since the two quantities n and λ when multiplied together are always going to produce the same result, that if we make n larger, we must make λ smaller and if we make λ larger n must be correspondingly smaller, so as to maintain the relationship that when the two are multiplied together they always produce our constant velocity, V.

Returning, therefore, to the consideration of short waves, we see that as we shorten the length of the wave we shall have higher numbers of cycles. We have already seen in Chapter I that radio waves are generated by passing electric currents along conductors, and to secure the maximum generation of radio energy we raise these conductors as high as we can into the air, such conductors then being called aerials.

The readiness with which we can erect stations operating on lower wavelengths is, therefore, bound up with our ability to cause alternating currents of higher frequency to flow in our aerial.

Primarily, radio waves are used for communication and this postulates that there shall be a sender who desires to make a communication and a receiver who is anxious to hear the communication. We, therefore, have two problems, that of designing suitable equipment for launching forth into the atmosphere our transmitted waves and that of picking up at a distance the very microscopic amount of energy reaching our receiving aerial and amplifying it so that it will work some sort of output device such as telephone, loudspeaker, television screen or automatic high speed Morse receiver.

Early Developments

Originally all wireless communication had been by means of Morse code, the method of signalling being merely to interrupt the transmission by means of a Morse key so that when the operator at the receiving station listened in he heard a continuous note interrupted so as to form the dots and dashes of the Morse characters.

The next great step forward was the application to the transmitted wave of telephonic modulation which enabled people to talk to one another by radio. We, who have got so used to broadcasting, probably find it difficult to appreciate the tremendous thrill which these pioneers experienced when they first heard each other's voices projected across space.

The new development of radio telephony opened up vast possibilities, and politicians, actors, and, in fact, all gifted talkers were quick to seize upon this new medium to enlarge their audiences. Every civilized country commenced the erection of broadcasting stations and it soon became necessary to have international conventions in order to avoid interference between the stations operating. To appreciate the magnitude of this problem, it is necessary to know a little of how radio waves are modulated by speech. As this has already been dealt with in other sections of this book, we will just recapitulate by saying that on all modulation systems, even up to the present day, the superimposing of the modulating or speech frequencies on the carrier wave involves a continual slight variation of the frequency of this wave during transmission.

The extent of this variation has been exactly calculated by mathematics and its limits are set up by the carrier frequency plus the highest modulation frequency and the carrier frequency minus the highest modulation frequency.

Modulation and Selectivity

Intelligible speech and music which is reasonably pleasant to listen to contains frequencies up to about 4,000 vibrations per second and it is therefore necessary when choosing the wavelength on which a transmitter sending out speech is to be used to see that its frequency will differ by at least 9,000 vibrations per second from the frequency of any other transmitter transmitting speech within range, otherwise there would be the

danger of the receiver receiving an unintelligible jumble of both transmissions at once.

If we have a transmitter sending out speech on a wavelength of, say, 3,000 metres, and operating on 100 kc/s., to achieve freedom from interference we can go down to 91 kc/s. for our next station and then down to 82 kc/s., and then we could go still lower to 73, 64, and so on. It is obvious, however, that the number of stations we shall be able to put up having frequencies lower than 100 kc/s. is very limited as the lowest frequency we can use is about 10 kc/s. corresponding to a wavelength of 30,000 metres. Our alternative, however, is to raise the frequency and it will be observed that there is no practical limit to the number of steps of 9 kc/s. which we can make when we go upwards.

When the great era of broadcasting began about 1924 and countries all over the world erected as many stations as they could, there was, obviously, a great scramble for wavelengths, and the fact that you could theoretically go up in frequency as much as you liked, but you could not come down, caused experimenters to concentrate on solving the problem of how to produce satisfactory transmitting and receiving sets using higher and higher frequencies and shorter and shorter wavelengths. In the broadcast receivers of the 1920's, wavelengths between 200 and 500 metres were always labelled " Short." Later on, when shorter wavelengths came into general use, it became necessary to re-label this " band " of wavelengths " Medium."

Having now seen the need for developing short wave systems of transmission and reception, we can now review the methods by which experimenters coped with the problem.

TRANSMISSION OF SHORT WAVES

Taking the transmission end first, it was found that normal oscillating valve circuits would produce oscillating electric currents down to wavelengths of about 5 metres. The technique of producing the carrier frequency and indeed of modulating it was merely a matter of continuing to use the same methods that worked on longer wavelengths. When it came to launching the radiation by means of an aerial, however, we were faced with the problem of transferring high-frequency energy from the oscillatory circuits to our aerial system. It was not possible to use a direct single wire connection as this itself would possess

sufficient inductance and capacity to cause serious loss of power. Fortunately, however, there is available a method of conveying high-frequency currents with very little loss from one point to another, the device used being known as a transmission line.

Transmission Lines or Feeders

These take three main forms—parallel wire feeders, concentric feeders and screened twin feeders. Parallel wire feeders essentially form a balanced system. They consist of two parallel copper conductors usually spaced about $\frac{3}{4}$-inch apart, each conductor being a fairly thick wire about $\frac{1}{8}$-inch in thickness. They are suitably supported so that their distance apart is rigidly maintained. If a number of factors which we shall go into later are properly attended to, we can feed the high-frequency energy into one end of this feeder and draw the same energy from the other end with only a negligible loss. The feeder, in a nutshell, solves our problem of getting the high-frequency energy from the valve generator to the aerial.

Aerial Systems

When we arrive at the aerial, the fact that we are using short waves very much helps us in our problem of designing a suitable system. In designing our short wave aerial system, we have to consider whether we wish to send out our energy in all directions, that is broadcasting, or whether we would do better to confine it in one particular direction. In the case of commercial stations erected for the purpose of sending messages to a definite receiver, it would obviously be a great advantage if we could send out our wave only in the direction in which the receiving station lay and prevent any wastage of energy going out in other directions. Use of short waves enables us to do this very effectively by making use of certain special aerial systems, called directional aerial systems.

Before we start discussing the more complicated directional aerial systems we will look into the way in which an aerial consisting of a single simple element works.

Basic Dipole System

The simplest form of short wave aerial which is very widely used is known as the dipole and consists of two wires lying in the same straight line as shown in the illustration, Fig. 1, the

length of these two wires being together equal to half the length of the wave which we desire to transmit. If we join our twin feeder to the centre of this dipole, as shown, we shall find, provided we have chosen the length of the two dipole wires correctly, that they will "resonate" at the frequency of the high-frequency current which is being fed to them from the transmission line. What is virtually happening is that we have a more or less closed field along the transmission line with the currents equal and opposite to one another in the two conductors all along their length.

Since we are dealing with alternating current it is, of course, evident that the actual current at any particular point along the line is varying from zero up to the maximum positive of our generated oscillation, then falling again to zero and rising to the maximum negative before falling again to zero. This process is happening continuously at the frequency of our oscillation which, in the case, say, of a 30-metre wave, will be by our formula, $V = n\lambda$, 10 million cycles per second or 10 Mc/s. At any particular point on the line, whilst the current at this point in one wire is, say, maximum positive, the current in the point opposite to it on the other wire will be maximum negative. Without going deeply into the mathematics of transmission lines, which are very complicated, we should appreciate that associated with the movement of current in a conductor is the movement of what scientists have called for a long time the electrostatic and electromagnetic fields.

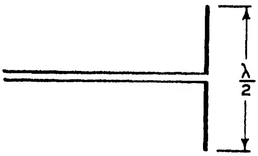


FIG 1—DIPOLE CENTRE FED FROM PARALLEL WIRE FEEDER

We can imagine when the particle of current or electron moves that it is moving with it electrostatic and electromagnetic lines of force which we can think of as thin elastic strands fastened to it. Conversely, these moving lines of force, if they intersect a conductor, will operate on particles of electricity or electrons in the conductor and cause them to move, thus creating an electric current in the conductor.

In a transmission line, the currents in the two wires and the electrostatic and electromagnetic fields between the wires form a balanced system. The movement of current along one wire helping, through the inter-connecting fields, the motion in the

other wire. Provided that we maintain the dimensions and spacing of the wires, energy will flow steadily for very considerable distances.

Let us now see what happens at the end of the line where it is joined to the dipole. At a particular instant, we shall have at this point of connection, say, positive current on one wire and negative current on the other. These currents will flow up the dipole wires to the free ends because they have nowhere else to go. Considering first the positive current; when this gets to the open end of the wire it will charge this open end to a positive potential, and when this potential gets sufficiently high, the further flow of current to the end of the wire will stop and the current will, as it were, recoil and go back to the centre. At the same time and in the same way, the negative current in the other wire piles up a strong negative charge at the far end of the other half of the dipole, and this also recoils to the centre. The two currents, when they arrive back at the centre, are opposite in direction to what they were before and still opposite to one another. They have travelled rapidly up and down the dipole wires and have given a considerable jerk to the electrostatic and electromagnetic lines of force which are always attached to them. This jerk, and all the jerks which follow, form the energy which travels out as radiation at its characteristic velocity from the aerial.

It is evident that the electrons forming the current in the dipole aerial must provide the energy which is radiated. The lines of force which have been jerked into motion in the manner indicated above react upon the electrons causing the jerks, and try to stop them. It is necessary, therefore, to feed power into the dipole to sustain the motion of the electrons and so to maintain radiation.

Radiation Resistance

As we already know, power in electric circuits is measured by multiplying the square of the current by the resistance of the circuit. It can be proved mathematically and measured by practical means that the dipole aerial behaves as if it were a resistance of approximately 80 ohms. This resistance is, in effect, a measure of the reluctance of the electromagnetic space medium (or ether as some people call it) to being jerked into wave motion. It is called the radiation resistance. It is, of

course, vastly greater than the actual D.C. resistance of the wires themselves. The dipole aerial is usually constructed of copper wires, or when the wavelength becomes quite short, it may take the form of a brass rod or tube. Any of these forms would naturally have a D.C. resistance of only a small fraction of an ohm. A dipole presents this resistance of approximately 80 ohms. only at the resonant frequency.

This resistance is the same whatever the frequency radiated, but of course the length of the dipole varies according to the frequency. Dipoles are used as short wave radiating aerials up to 15 or 20 metres or so, and since they are half a wavelength in length a dipole radiator of 15 metres would be 7·5 metres or about 8 yards long. At the other end of the scale, dipoles have been constructed to radiate down to a wavelength of about 10 centimetres or less, so that it is literally possible to carry a half wave aerial for these wavelengths in the waistcoat pocket.

Radiation Diagrams

When we come to consider the direction in which radiation goes out from an aerial, we find it helpful to make a pattern or diagram that we can use when designing equipment. In this, we represent our aerial by a dot in the centre of our paper and then we draw out a number of radii from this dot and mark along these radii points at which signal strength reaches a certain value, Fig. 2 (a) shows such a diagram drawn for a dipole aerial, and is known as a polar diagram. When we consider this diagram, we can see that it really only represents signal strength at points on a plane which contains the dipole. That is to say, if the dipole is mounted horizontally, we can see that the greatest radiation goes out either way along the line at right angles to the dipole rods and passing through the centre of the dipole. Practically no radiation takes place in the direction in line with the dipole. A dipole mounted in this position is said to give rise to horizontally polarized waves. If we were to turn the dipole up and stand it on its end, as it were, it would give rise to vertically polarized waves. Our lines of force will be shaken up and down instead of from side to side.

We have just said that this diagram gives the distribution of radiation over the surface of a plane which contains the dipole. Radiation, however, extends out in all directions from the dipole and we could select numbers of planes at varying angles passing

through the centre of the dipole and draw polar diagrams showing the distribution of energy in all these. If all possible planes were combined together, we should then have a polar diagram in three dimensions. For a given field strength, we could construct a solid figure which would show at what distance from the dipole in any direction in space we would obtain this given field strength. It is usually, however, sufficient for the purpose of making calculations to consider one particular plane at a time. This plane would normally pass through the transmitting aerial and the receiving aerial. Out of all the possible further planes that we might consider, we will select one as presenting special interest. This is the plane which lies at right angles to the dipole wires and passes through the centre of the dipole. The radiation pattern in this plane for a simple dipole is found by experiment and by mathematical calculation to be a circle, and we have shown this for ease of comparison in Fig. 2 (b).

The diagrams shown are the polar diagrams for dipoles situated in free space, that is to say, dipoles in which the radiation patterns are not interfered with by any conducting objects close to them. Such dipoles are rarely met with in practice. An aerial forming part of a ground station transmitter will obviously be somewhere near the ground and will, therefore, have a reflecting surface below it. Waves extending out from the dipole will strike the ground and be reflected so that at some distant point we shall be receiving a direct ray from the

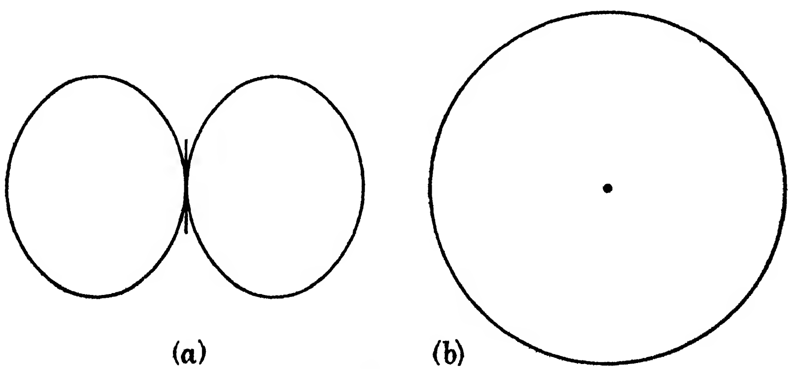


FIG. 2.—POLAR DIAGRAMS OF HALF-WAVE DIPOLE.

(*a*) In plane of dipole.
(*b*) In plane at right-angles to dipole.

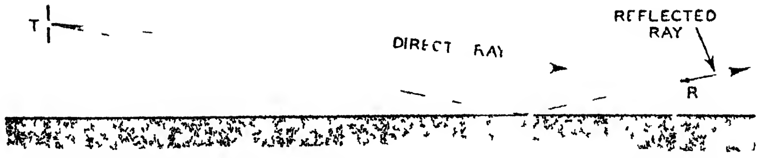


FIG 3—TRANSMITTING DIPOLE SITUATED CLOSE TO REFLECTING SURFACE

dipole aerial and a ray reflected from the ground, the effect being as shown in the diagram, Fig. 3. Even an aerial mounted on an aircraft will have its radiation pattern modified by the proximity of the aircraft itself.

Reflectors

We have mentioned the earth's surface as a reflector, but this is not the only type of reflector which can affect the radiation pattern of an aerial. If we erect an aerial at some point and then place a metallic screen behind it, we can prevent radiation from it going backwards through the screen and increase the radiation going forward in the opposite direction. Such a surface situated behind an aerial acts as a sort of mirror and just as in the case of a mirror, we think we see in the mirror an object which is situated in front of it, so we can visualize that an imaginary dipole is situated behind the mirror at a point opposite to the actual dipole. This imaginary dipole may be assumed to radiate in the same way as the real dipole in front of the mirror, and therefore, at some distant point in front of the mirror, we shall receive a combination of the radiation sent out from the real dipole and that which reaches us from the imaginary or reflected dipole behind the mirror.

Now we know that the radiation from a dipole is of a wavelength equal to twice the length of the dipole, provided we have designed our equipment correctly and are feeding the correct frequency to the dipole. We can, therefore, draw out a picture which will represent the wave leaving the dipole, and we can see that if we have, say, a crest of the wave at the dipole, we shall have another crest λ metres in front of the dipole and another crest $2 \times \lambda$ metres from the dipole. Considering now the radiation from the reflected mirror image, this will produce its crests also λ metres in front of it, $2 \times \lambda$ metres in front of it and $3 \times \lambda$ metres in front of it, and so on. We can see that if we choose the distance of our dipole aerial from the

reflecting surface correctly, we can arrange so that the crests arriving from the real aerial come at the same points as the crests arriving from the reflected aerial, and we shall thus get an increased signal. The two waves are said to be arriving in "phase." An incorrect positioning of a reflector could cause the reflected wave to arrive out of "phase" and practically blot out the direct radiation.

A warning should be interjected here to the effect that this explanation is really an over-simplification and other factors are present which make calculations more complex so that usually designers fall back on making experiments to determine the best position for reflecting screens.

With the longer of the short waves, say from one metre upwards, it is not a very feasible thing to employ a plain metallic screen as a reflector and what is actually done is to use a resonant wire which normally has a length approximately $\frac{\lambda}{2}$. It is not necessary, however, to work in exact multiples of $\frac{\lambda}{2}$. A reflector can be situated quite close behind a dipole and constructed of such a length that energy re-radiated from it will be in "phase" with the radiation from the dipole. It is probably possible to work out the length of reflectors mathematically, but the equations are very complex and, in any case, polar diagrams can be fairly easily measured in practice so that usually the length of reflectors is determined by a process of trial and error. A simple form of directional aerial is, therefore, a single dipole with a reflector of the correct length situated at the correct distance behind it. More elaborate directional systems consist of a dipole wire with a curtain of reflectors situated in the form of a parabolic arc behind it, in the same way as a motor car headlamp bulb has a parabolic reflector behind it to produce a beam.

Aerial Arrays

Another method of securing that radiation shall take place in one direction only is to feed a number of dipoles simultaneously. All are situated in the same plane, and fed by means of a special feeder system from our transmitter. "Arrays," as these systems of dipoles are called, may contain up to 8 or even more such dipole elements. To secure any particular radiation pattern, these have to be placed and rigidly held in the correct position.

The theory of operation of an array of this type can be understood if we consider a receiver placed at a considerable distance from the array. It will receive its signal from the various dipole elements forming the array along lines as indicated in Fig. 4.

It is evident, when we consider this diagram, that the distances of each dipole element from our receiver are almost exactly the same at a position vertically in front of the array, say at P, but the actual distance from the receiver of the individual elements of the array will differ by the amounts a, b, c, if the receiver is situated at, say, the point Q instead of at the point P in front of the aerial. Waves reaching the receiver will arrive "in phase" when the receiver is at P, but somewhat out of phase when the receiver is at Q.

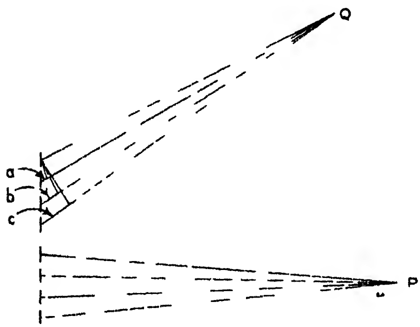


FIG 4—BEAMING OF RADIATION BY ARRAYS

As this treatise is only an outline, we will not go further into the polar diagrams associated with this type of array beyond saying that it is possible to get a concentration of energy radiated from the system amounting to about seven or eight times as much in front of the array as is sent out sideways or backwards. Typical polar diagrams for arrays of this kind are shown in Fig. 5. It can be seen that this beaming of the radiation from the transmitter in the desired direction results in a very great saving in the power required at the transmitter to produce a signal of given strength at the receiver.

Methods of Feeding Aerial Arrays

Going back to the question of feeding a dipole with current from the feeder, we have considered the system where a parallel wire feeder is joined directly to the two elements of the dipole at the centre. We have said that the current rushes up the two wires (or rods) and charges the ends of these to a high potential. We can represent the distribution of current and voltage in the dipole by means of diagrams. The current distribution is shown in Fig. 6 (a), and voltage distribution in Fig. 6 (b). Obviously it will not be possible for us to have a current flowing at the end

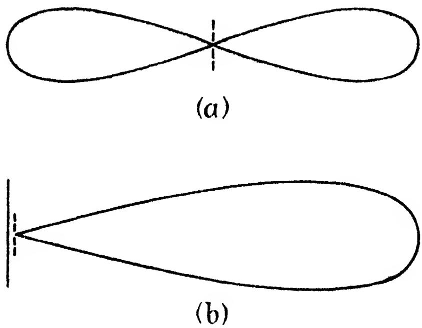


FIG. 5.—APPROXIMATE POLAR DIAGRAMS OF 4-DIPOLE ARRAY

(*a*) Without reflector
(*b*) With reflecting screen behind array (secondary lobes not shown)

of the dipole, because the electrons forming the current cannot leave the wire and escape into space. At the end of the wire, therefore, we have a high voltage or what is often described in wave theory as a voltage node. The state of affairs at the centre of the dipole, however, is that current is highest at this point because we have to secure the maximum flow of electricity at this point to charge the whole length of the wire. We, therefore, have a current node at the centre.

In order to supply the dipole from a feeder, if we are connecting it to the centre of the dipole, we must employ a feeder which will deliver a high current at relatively low voltage. We could, alternatively, feed the dipole from the end, but in this case we should apply a high voltage with a relatively low current. Since our whole half-wave aerial is really a wire capable of resonating at the wavelength at which we have chosen to transmit (because its length is half this wavelength), all we are doing, when we connect a feeder to it, is to set the electrons in the wire moving up and down it so as to form voltage nodes at the ends and current nodes at the centre. If, then, we feed from one or other end we shall have to join together the gap which we had between the two wires when we feed from the centre, so that the current can flow straight down the whole length. This form of aerial is, therefore, more properly called a half-wave

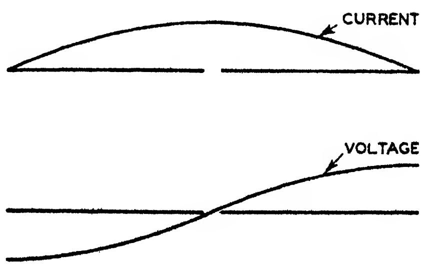


FIG. 6.—CURRENT AND VOLTAGE DISTRIBUTION CURVES IN DIPOLE.

radiating element rather than a dipole, which leads the reader to expect that there will be two separate conductors.

Many other methods have been devised for launching radiation. A type of aerial, possibly even simpler than the dipole, is sometimes called a unipole or quarter-wave radiator. One or more of these are usually employed projecting from a reflecting surface, as shown in Fig. 7. From the point of view of calculating their effectiveness, they may be thought of as possessing mirror images extending behind the reflecting surface so as to make each unipole in effect into a dipole. The same reasoning which applies to the dipole arrays can be applied to unipole arrays; with the exception that virtually no radiation goes out behind the screen.

When we come to consider aerial arrays situated, not in free space, but near the earth's surface, that is arrays which are used for launching the radiation from ground station transmitters as opposed to those carried in aircraft, we can design our aerial systems with a view to projecting the radiation in certain directions. This is usually desired for commercial point-to-point communication, and the Empire Short Wave Beam System furnishes a good example. This employs a parabolic curtain of reflecting wires as indicated above. Alternatively, for broadcasting purposes, we might desire to send the radiation out in a circle all round the station.

For a television transmitting aerial, for instance, a more or less uniform distribution of field strength is required at all points on the surface of the earth around the station. We, therefore, use an aerial system which has a radiation polar diagram in the form of a circle in the horizontal plane. We must also think, however, of the radiation which shoots out upwards from the aerial at all sorts of angles and try to design our aerial system to avoid sending too much of our precious radiation into the sky. Now it can be established experimentally and confirmed by mathematical calculation, that the vertical polar diagram of an aerial situated near the earth's surface consists of a number of lobes taking a form somewhat as shown in Fig. 8.

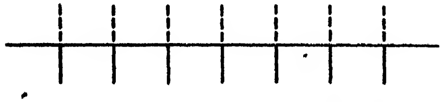


FIG. 7.—ARRAY OF UNIPOLES MOUNTED BENEATH REFLECTING SCREEN.

In order to obtain the maximum radiation at a low angle, it is necessary

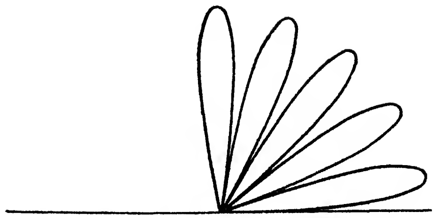


FIG 8—TYPICAL VERTICAL POLAR DIAGRAM OF AERIAL SITUATED NEAR REFLECTING SURFACE

to raise the aerial as high as possible above the reflecting surface of the ground beneath. That is the main reason for the selection of high ground for the location of the transmitter, supplemented by the erection of poles or masts to support the actual aerial array itself.

RECEPTION OF SHORT WAVES

Having dealt at some length with the launching of radiation from the transmitter, we will now leave this and look into the methods used for picking up radiation at a considerable distance from the transmitter.

Here our problem is to erect an aerial which will intercept the waves radiated from the transmitter so that they will act on the electrons in the aerial elements and set them in motion. What we have to do then is to conduct the currents thus produced to our receiving equipment. We can use feeder lines, connected in a similar manner to those used at the transmission end, for linking up our receiving aerial to the actual box containing the receiving equipment.

The Reciprocity Theorem

The fact that similar equipment is used for both transmitting and receiving radiation has led to the development of a theorem known as the Reciprocity Theorem for assisting the design of suitable receiving arrays. The Reciprocity Theorem really states that if an array of radiating elements has a certain polar diagram when used for transmission, it will develop a sensitivity of the same pattern when used for receiving radiation. We can, therefore, imagine the various arrays, which we have discussed, to have polar diagrams of reception similar to the transmission polar diagrams. Thus, when designing two-way communication between stations we pay attention to the aerial system at the receiver end and arrange that it picks up its

maximum amount of energy from the direction in which the transmitter lies. This has a two-fold advantage. We shall secure the maximum voltage induced in our receiver feeder from the transmitter and we shall limit to a considerable extent any interfering voltages which may reach the aerial from sources in other directions than that in which the transmitter lies.

The Reciprocity Theorem can be applied to systems of radiating or receiving elements according to whether the array under consideration is used for transmission or reception, but we must not regard it as completely true when we come to consider the feeder systems linking the various aerial elements together and the further feeders connecting the arrays to the transmitter or receiver as the case may be.

Matching

Before we consider this further we have to understand what we mean by matching. To do this we must digress a little and go back to the idea of the feeder. We can visualize a feeder. either parallel wire or concentric as the case may be, and think of ourselves feeding an oscillating current into it from a suitable source. This current will flow down the feeder away from the end at which it is fed, which we will call the input end, until it reaches the far end or output end. At this point, the energy is delivered to a further device. On the transmission side it will be an aerial or aerial array and we have to design the whole system so that all the energy that we send into the feeder can be received by the output device.

In order to be able to calculate the electrical data necessary, to enable us to do this we have to introduce a special conception; this is a feeder of infinite length. We can then, of course, feed energy into this and not bother about the far end because that being at infinity is so far away that the energy will never get there. We then make calculations to determine how the near end of the feeder behaves.

What we really want to know is whether, when we connect our feeder to the transmitter, it will behave as if we had connected to the transmitter say a resistance or a condenser, or an inductance. If the feeder behaves as if it were one or other of these simple electrical devices we then say that the feeder "looks like" one of these things or a combination of them. Combinations of resistance and inductance or resistance and capacity

are called impedances and in the special case of an infinite feeder the impedance which this feeder " looks like " at its input end is called its characteristic impedance.

The characteristic impedance of a feeder is determined by its geometrical dimensions. In the case of a parallel wire feeder, these will be the diameter of the wires and their distance apart. In the case of a concentric feeder, the characteristic impedance will depend upon the external diameter of the centre conductor and the internal diameter of the outer braiding or tube. The impedance will also be affected by the material which is used for filling up the space between the inner and outer conductors.

As we want to convey energy from the transmitter to our aerial, we select a feeder which has a characteristic impedance equal to that of the output of our transmitter. The feeder and the transmitter are then said to be " matched." When they are connected together energy can flow from one to the other in a steady stream. When we come to the far end of the feeder, which is now not at infinity but only at a convenient distance away, say at the top of the aerial mast, we have to arrange that the impedance of the aerial array which we connect to it is equal to the characteristic impedance of the cable. A little consideration will show the reason for this. It is obvious that the device which has an impedance equal to the characteristic impedance of the cable would behave in the same way when connected to the end of the cable as a further length of the cable stretching out to infinity. In order to ensure a continuous flow of energy from the cable out at its far end, we can therefore connect to it an impedance equal to its characteristic impedance at any point along the cable.

" Mis-match "

As, however, things may not work out just as we plan, we must investigate what happens if we are unable to achieve this ideal condition. Suppose that for some reason or other the impedance of the aerial array differs from the characteristic impedance of the cable; then, when we connect the far end of the cable to the array, we shall have what is known as a " mis-match " at the point of connection. Without going elaborately into the mathematics of the affair, we can say that if a " mis-match " occurs, the aerial system will not accept the whole of the energy flowing from the cable but only a part of it; it will

reflect the remainder back along the cable towards the input end. We shall, therefore, have in the cable energy flowing steadily down it, and superimposed on this we shall have the reflected energy returning. When this energy gets back to the input end it will again be reflected to the far end and so on, and we shall have on the feeder what are known as standing waves as opposed to the waves of energy which are flowing through the feeder. The energy of the standing waves will eventually be converted into heat in the feeder and will represent waste of our transmitted energy. To eliminate, or perhaps we had better say, to minimize this effect special devices known as stubs are used situated close to the output end of the cable and they consist of impedances whose values are so chosen that they balance out the " mis-match " at the junction.

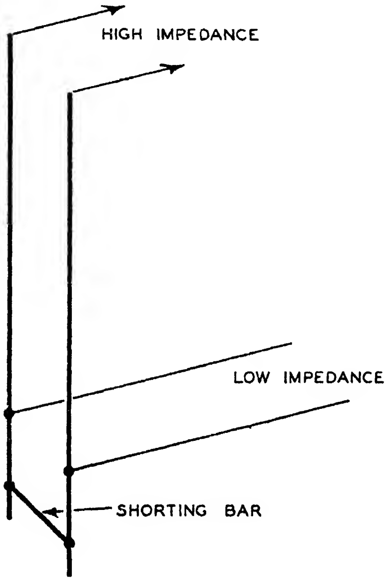


FIG. 9. – IMPEDANCE TRANSFORMER.

Matching Transformers

An alternative device which may be used for the same purpose or even in conjunction with stubs is a matching transformer. This may consist of a short length of parallel wire feeder short-circuited at one end and connected as shown in Fig. 9; or it may consist of a quarter wavelength of a feeder of specially chosen characteristic impedance.

The choice of a quarter wavelength has a special significance and has so many practical uses that it may be interesting to give it a little special consideration. If we select a feeder a quarter of a wavelength long, it can be proved by mathematical calculation and confirmed experimentally that its input impedance multiplied by its output impedance is equal to the square of its characteristic impedance. Expressed as a formula :—

$$Z_1 \times Z_2 = Z_0^2$$

where Z_1 is the input impedance, Z_2 is the output impedance, and Z_0 is the characteristic impedance. Suppose now, we see just what the implications of this formula are for some special cases. Take first of all the case of a quarter wavelength of a feeder in which the far end is short-circuited as shown in the illustration Fig. 10(a). In this special case Z_2 will be zero. By our formula,

$$Z_1 = \frac{Z_0^2}{Z_2} = \frac{Z_0^2}{0} = \infty$$

So we see that a quarter wavelength of feeder, short-circuited at the far end, behaves as if it were an infinite impedance and, consequently, when such a short-circuited length of feeder is connected across our feeder system at any point it will not withdraw any current from the feeder or affect the feeder in any way as it has infinite input impedance. This fact is made use of when we want to support the feeder. All we need to do is to construct a quarter wavelength of feeder of some strong material and short-circuited at the far end, then connect it to the feeder at the point we require to support it. Supposing now we consider another case of a quarter wavelength of feeder in which the output end is open-circuited. In this case, $Z_2 = \infty$. From our formula

$$Z_1 = \frac{Z_0^2}{\infty} = 0$$

If, therefore, we connect such an open-circuited quarter wave to any point in our feeder, as shown in Fig. 10(b), we shall virtually be short-circuiting the feeder at this point and absorbing all the energy flowing along it. Variations of this theme have produced numbers of interesting devices, as we can, of course, use a switch at the end of our quarter wave and alternatively short-circuit and open-circuit our feeder for various purposes such as interrupting transmission, etc.

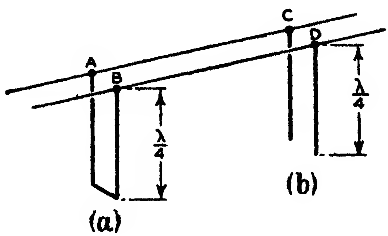


FIG. 10.—USE OF STUBS.

(*a*) Short-circuited quarter-wave stub reflecting open circuit at points A and B.

(*b*) Open-circuited quarter-wave stub reflecting short circuit at C and D.

If our output impedance has a value somewhere between these two extremes of zero and infinity we can find the corresponding input impedance from our formula. Suppose we have a feeder with a characteristic impedance Z_1 and we want to deliver energy to a load which has a different impedance, Z_2, we use the quarter wave transformer for connecting the two together. This will consist of a quarter-wave of " line " which will have a characteristic impedance Z_0 given by the formula $Z_0^2 = Z_1 \times Z_2$, that is to say, it will have a characteristic impedance equal to the square root of the impedance of our main feeder cable multiplied by the impedance of the load. Knowing this value, we can consult some tables and find out the geometrical dimensions, i.e. spacing and diameter of wires of a feeder which will give us this characteristic impedance.

We hope that the above remarks have shown the necessity for matching and indicated some of the ways in which it is done. Matching is designed to avoid reflections where the feeder delivers its energy to the load. In the case of transmission, they are situated at the point where the feeder joins the aerial. When we come to the receiving end, however, energy is flowing from the aerial to the receiver and we have to locate our matching devices where the feeder joins the receiver so as to avoid energy being reflected back from the receiver along the feeder wires connecting it with the aerial.

We have now followed the course of our high-frequency energy in its various forms from the transmitter to the transmitting aerial and across space to the receiving aerial and thence through the receiver feeder system to the receiver. It now remains for us to look at this receiver and see how it amplifies the energy delivered by the feeder and makes it available for operating a loudspeaker or any other device for which it may be required.

Receiver Design

Receivers follow more or less normal lines and comprise usually high-frequency stages followed by frequency changer, intermediate frequency stages, second detector, low-frequency amplifiers and output device. Sometimes there is no intermediate frequency stage, that is to say, the receiver is a straight receiver and not a superheterodyne. Sometimes there is no high-frequency stage; the input in this case being direct to the

frequency changer. In certain cases of television receivers and possibly in other applications, L.F. amplification may not be required, the output of the second detector being sufficiently strong to work the device for which the receiver is designed.

Whatever system is used, it is necessary to match the feeder which conveys energy from the aerial as nearly as possible to the first valve used in the receiver. This matching is usually done by tapping the cable on to some point of the tuning inductance used in the grid circuit of the first valve. The connection being arranged as shown in Fig. 11.

Valves have recently been developed which have specially low inter-electrode capacities. Quite satisfactory amplification can be obtained down to wavelengths of the order of one metre or so. Anode and grid oscillatory circuits are usually arranged so that any stray capacities in the valve form part of the tuning capacities of the oscillatory circuits and so do not reduce the available voltages. When we come, however, to considering amplification at these frequencies, we find that the input impedance of the grid circuit of the first valve has a very much lower value than one might expect from a purely capacitative effect. In fact, if there were only the capacity effect to consider we could balance it out completely and we should theoretically need no energy to operate the valve.

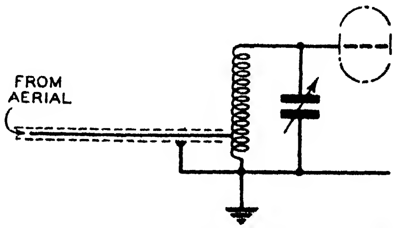


Fig. 11.—Receiver Concentric Feeder connected to Tapping Point on Grid-Tuning Inductance.

This, however, is not so because inside the valve, as we have already seen in the chapter on valves, we have a stream of electrons flowing past the grid. Whilst we can prevent any of these electrons alighting on the grid by applying a negative voltage to it so that there is no actual flow of grid current, we still have to expend energy when we wish to change the voltage of the grid from one value to another. The reason for this is that when we apply a voltage to the grid, especially an oscillating voltage, this voltage is attempting to change the velocity of the electrons passing through it, and does, in fact, change it. The work required to do this has to be supplied from the input oscillatory circuit, the driving power necessary being picked up

from the aerial and supplied through the connecting feeder.' At frequencies of around 200 Mc/s, the input impedance of the grid circuit of a valve due to this cause may be as low as about 900 ohms.

The design of the receiver has to take account of the effect that stray capacities have on tuning circuits, and such circuits are arranged so that these stray capacities form part of the tuning capacity. Often no variable condenser is used for tuning; tuning capacity being provided entirely by strays. Variation of the resonant frequency is then obtained by varying the inductance of the tuning coil concerned. This can be done by means of a movable core which may consist of a conductor such as brass, or a magnetic medium of high permeability. At high frequencies, these permeable alloy cores are composed of a mixture of metallic dust embedded in some non-conducting powder which can be compressed to form a solid "dust core." Once we have converted the frequency at which we receive signals to the intermediate lower frequency by our frequency changer the design of the Short Wave receiver does not differ materially from that of receivers used at longer wavelengths.

CHAPTER XXII

THE CATHODE-RAY TUBE

THE cathode ray effect formed the subject of experiment by outstanding scientists of the calibre of Faraday and Crookes and as far back as 1908 its use for television reproduction was proposed by Campbell Swinton. The apparatus used for the early experiments had little in common with the modern cathode-ray tube but the pioneer investigators did succeed in establishing certain basic principles which paved the way for subsequent development.

By connecting the output from an induction coil to electrodes arranged at each end of a glass tube and steadily pumping the air from the tube, the pioneers noted a series of remarkable phenomena as the process of evacuation proceeded. Initially, in this experiment, the whole tube is filled with a soft glow which undergoes a series of changes as the air pressure is reduced. Finally, at very low pressures, the luminosity in the tube disappears and the walls of the tube shine with a green fluorescence which was shown to be due to rays from the cathode impinging on the glass. Subsequently, it was shown that the rays could be deflected by a magnet outside the tube and that deflection could also be caused by electrostatic fields. The rays were also shown to possess no appreciable inertia. These discoveries were as important as they were interesting and it is curious that they found no practical application for several decades. X-rays, which are literally an off-shoot of the cathode ray, were followed up and exploited with relative rapidity, but the C.R. tube made no real progress until well into this century.

In the modern electrostatic C.R. tube, the cathode ray comprises a stream of electrons which can be focused to a fine point and deflected at will by means of a system of electrodes all of which are enclosed within a conical glass vessel of the type shown in Fig. 1. On the inside of the flat end of the tube is

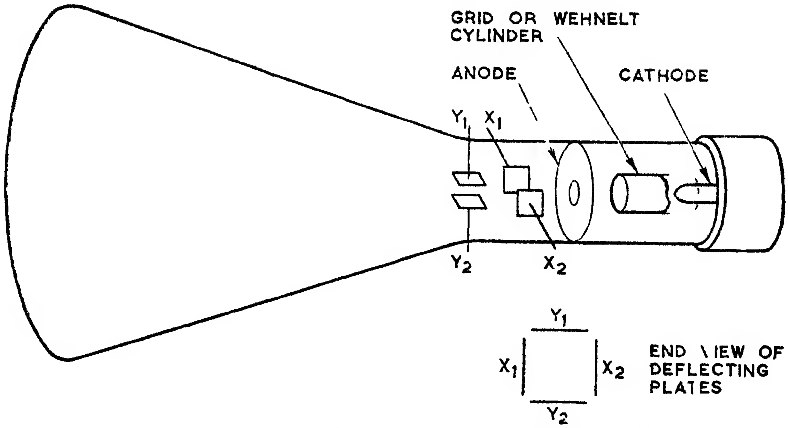


FIG. 1 — ELEMENTS OF THE SIMPLE ELECTROSTATIC CATHODE-RAY TUBE

deposited a chemical possessing the property of glowing or, fluorescing, under the impact of high velocity electrons. Movement of the ray across the end of the tube, or screen, can thus be observed with the eye and hence any phenomena that can be translated in terms of movement of the ray can similarly be visually observed.

When considering the construction of the C.R. tube in detail, it will be noted that the principle is basically the same as that of the thermionic valve. The source of electrons is a filament, or indirectly heated cathode, which is surrounded by a metal tube, shield, grid or Wehnelt cylinder as it is variously termed. The grid is maintained at a negative potential with respect to the cathode and therefore has the effect of repelling the electrons and tending to concentrate them. A short distance from the cathode is the anode, comprising a circular disc with a small hole in the centre. This anode, or accelerator, is maintained at a high positive potential with the result that the emitted electrons rush towards it at very high speed. Assisted by the concentration afforded by the grid, a large number of the electrons pass straight through the hole in the anode as a narrow beam, finally striking the fluorescent screen at the end of the tube and dissipating their energy in the production of a glowing spot. The beam of electrons may now either be deflected by external magnetic forces which will be discussed later, or by two pairs of plates arranged inside the neck of the tube immediately following

the anode. One pair of plates is known as the " X " plates and voltages applied to them deflect the beam in the horizontal plane, while the other pair of plates is known as the " Y " plates which are at right-angles to the X plates to deflect the beam in the vertical plane.

These, then, are the elements of the simple electrostatic C.R. tube—a cathode, grid, anode with a hole in the centre, two pairs of deflector plates and fluorescent screen, all contained within a flask-like glass container. There are many variants of this basic design. Some tubes are " hard," some are gas-filled to assist focusing ; some have two or three anodes and specially designed deflecting plates, others have a minimum of electrodes and employ external magnetic means for focusing and deflection ; screen diameters vary from 1½ inches to 15 inches, dependent upon the purpose for which they are designed. All these designs will be considered in their turn, but the elementary electrostatic tube of the type outlined provides the simplest means of explaining the basic principles and operation of the C.R. tube.

PRINCIPLES OF OPERATION

The simple electrode arrangement of Fig. 1 now exists commercially only in the form of the gas-filled tube. Such " soft " tubes are low voltage types requiring a heater supply of 2–4 volts, anode potential of 500–1,000 volts and a negative shield bias of 5–50 volts. Control of the grid potential is the primary means of focusing the spot which, when properly focused, will be 0·5–1·0 millimetres in diameter.

Assuming now that the operating conditions are correct and the tube is " on," let us consider the effect of applying a potential across the X plates. Dependent upon the sign of the applied voltage, the cathode ray will be repelled by one X plate and attracted by the other. In Fig. 2, plate X_1 is positive and plate X_2 is negative, with the result that the electron beam is deflected towards X_1. The movement of the ray at these plates will be apparent as a movement of the fluorescent spot of the screen, the degree of movement on the screen being enlarged in proportion to the length of the ray. If now the connections to X_1 and X_2 are reversed, the spot will move across to the

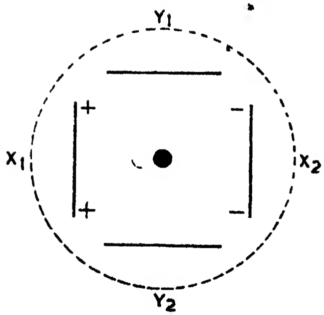


FIG 2.—A POSITIVE POTENTIAL ON PLATE X_1 CAUSES THE CATHODE RAY TO SWING OVER TO THAT PLATE

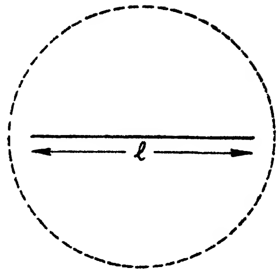


FIG 3.—RAPID MOVEMENT OF THE SPOT FROM SIDE TO SIDE RESULTS IN THE APPEARANCE OF A STEADY LINE ON THE SCREEN, THE LENGTH "l" OF WHICH IS DIRECTLY PROPORTIONAL TO THE DEFLECTION VOLTS

opposite side of the screen. When an alternating voltage is applied to the X plates, therefore, the spot will clearly move from side to side in step with the frequency of the alternations. Because of the afterglow in the fluorescent screen and the rapidity of the movement, the effect to the eye will be the appearance of a steady line across the screen (Fig. 3). The length of the line will be directly proportional to the voltage applied to the deflecting plates.

Suppose while this line is being traced out on the C.R. tube a D.C. potential is applied to the Y plates. It is obvious that the spot must tend to respond to the force thus exerted on the ray as it passes between the Y plates. This response will take the form of shifting our line bodily up or down on the screen, depending on whether Y_1 is positive or negative. But what will happen to the spot if instead of D.C. on the Y plates we apply an alternating voltage? We will assume for the moment that both voltages (the X and the Y) are derived from the power mains and are therefore both sinusoidal and are of the same frequency and phase.

Two forces are now acting on the ray at the same time and its movement will be proportional to the resultant of those forces at any instant. Our line on the screen will, therefore, assume a new position making an angle with the horizontal which is governed by the relative value of the deflecting forces. If the alternating voltages applied to the X and Y plates are equal,

the angle of the line on the screen will be 45 degrees (Fig. 4*a*). By variation of the relative values of the voltages applied to the X and Y plates the angle will correspondingly become greater or less.

The straight line on the screen is preserved only while the two applied voltages are of the same phase. Where there is a phase difference, the resultant of the forces acting on the ray differs from instant to instant with the result that the spot traces out an elliptical path ranging from the straight line already discussed when the phase angle is 0 degrees to a circle when the phase angle is 90 degrees.

This experiment takes us into the realm of Lissajous' figures which are invaluable for the determination of phase angle, power factor, etc. It is not proposed to discuss Lissajous' figures further here and those interested will find the subject exhaustively treated in standard works on the employment of C.R. tubes.

Time Base Circuits

For most practical applications of the C.R. tube the requirement is to observe the variations of phenomena in relation to time. To meet this requirement linear time bases have been developed, the object of which is to cause a regular pre-determined sweep of the spot from A to B (Fig. 5) with the additional requirement that on reaching, B the spot shall instantaneously return to point A in readiness for the next cycle.

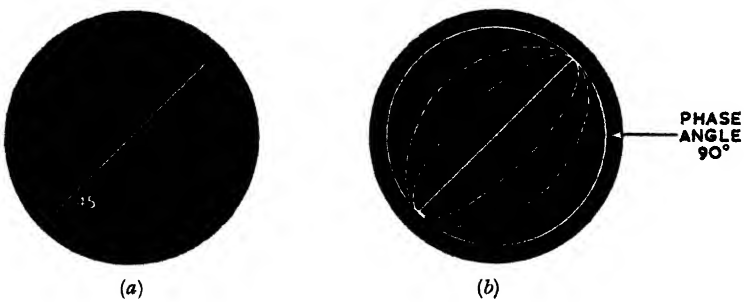


FIG. 4.—EFFECT OF APPLYING ALTERNATING VOLTAGES TO THE DEFLECTION PLATES.

(*a*) When equal alternating voltages are applied to X and Y plates simultaneously the line on the screen assumes an angle of 45°.

(*b*) When the voltages applied to the X and Y plates differ in phase, the spot traces out an ellipse which becomes a full circle when the phase angle is 90°.

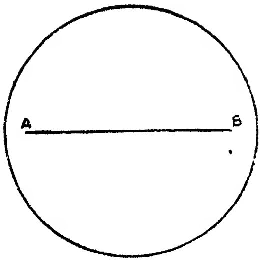


FIG. 5 —A REGULAR SWEEP IS REQUIRED FROM A TO B.

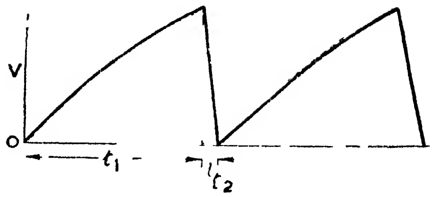


FIG. 6.—SAW-TOOTH WAVE-FORM FROM C.R. TUBE TIME BASE.

The spot can be caused to move in the required manner by that application to the plates of a voltage having a " saw-tooth " wave-form as illustrated in Fig. 6. The ideal time base would provide an output with a wave shape conforming to the dotted line in Fig. 6, as opposed to the practical output which is indicated in somewhat exaggerated form by the solid lines. It will be seen that the solid line, representing rise in volts, is slightly curved where the ideal would be perfectly straight. This is because the charging of a condenser is the means of providing the voltage rise and the rate of increase of P.D. across a steadily charging condenser is exponential. The other departure from the ideal is more important. This is that the drop of volts from maximum to zero is not instantaneous but takes a finite time which is represented by t_2 in Fig. 6. The time taken for the forward deflection of the spot is t_1 while t_2 is the time taken for the return or " flyback " of the spot for the next cycle. Ideally, of course, t_2 should be zero, but this is unattainable in practice.

Producing the Saw-tooth Wave-form

The problem of producing a saw-tooth wave-form is not difficult. In the simplest design, advantage is taken of the

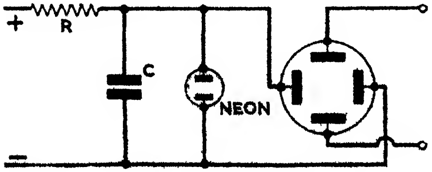


FIG. 7.—ELEMENTARY NEON TIME BASE CIRCUIT.

voltage rise derived from the steady charging of a condenser through a resistance R (see Fig. 7). The P.D. across the condenser will steadily build up but, as already noted, in accordance with an exponential law so that the rate of increase will be as shown in Fig. 8. This charging curve is useful for time base purposes up to the point marked M following which point, the curve makes too great a departure from the linear rate of increase desired.

The voltage rise across a charging condenser will, then, provide our forward sweep and to obtain the sudden fall in P.D. to give us the flyback obviously requires the condenser to be short-circuited when it has reached the specified voltage. For a time base circuit, this process of steady charge and immediate discharge must be continuous. The earliest successful means of achieving this object made use of the neon lamp. This has a definite striking voltage (150–170 volts) and takes no appreciable current until this P.D. is reached. When the striking voltage is attained, however, the neon flashes and there is a heavy current flow which continues until the pressure falls to too low a level to maintain the discharge. This is the biggest drawback of the neon lamp because the current discharge cannot be maintained when the P.D. falls below 130 volts. We, therefore, have available for effective use as a time base about 40 volts only—the difference between the striking and extinction voltages of the neon. This is represented by that part of the curve between M and E in Fig. 8.

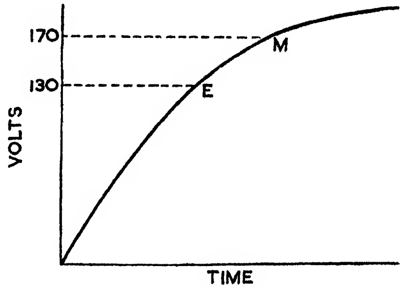


FIG 8—ILLUSTRATING THE NON-LINEAR RATE OF CHARGE OF A CONDENSER THROUGH A RESISTANCE.

With a C.R. tube having a sensitivity of 1 mm/volt, i.e., 1 millimetre movement of the spot on the screen per volt applied to the deflecting plates, this output from our neon time base would give us an image little more than 1½ inches wide. It is possible to amplify the output but the neon possesses the further disadvantages of being unsuitable for frequencies above 10 kc/s. and is no longer adopted for practical time base circuits.

Gas-filled Relays

A more efficient means of discharging the condenser is provided by the mercury vapour relay. This is a triode into which mercury vapour has been introduced and in its initial operation, it behaves in a similar manner to a triode in that the grid exerts a very large measure of control over the current flow through the tube. This control is expressed as a figure representing the "grid control ratio" and is usually about 20. Practically interpreted, this ratio implies that for each volt negative on the grid 20 positive volts are required on the anode before control is lost. When the anode volts reach the requisite figure the tube strikes and there is a very heavy current flow which cannot be stopped until the anode potential drops to about 15–20 volts, when the mercury vapour de-ionizes. The grid exerts control over the potential at which the tube will strike, but has little control once current begins to flow, regaining control once the anode potential falls below the level required to maintain ionization of the mercury vapour.

These characteristics of the mercury vapour relay clearly offer much greater scope for time base use than the neon. With a grid bias of 10 volts the anode volts will rise to 200 before the tube strikes. Discharge will continue until the anode potential falls to 20 volts. We have, therefore, a deflection voltage of about 180 volts available which is sufficient to provide a reasonably sized image on a sensitive gas-filled C.R. tube.

Inert gas filling, such as argon, helium and neon is used in triodes to serve the same purpose as the mercury vapour relay. The results obtained are better than those possible with the mercury vapour type, particularly for high speed working, but the principles of use are similar.

Improved Time Base Circuits

It has already been seen that the rate of charge of a condenser through a resistance is not constant but follows an exponential law. This drawback can be largely overcome by the substitution of a pentode valve for the resistance, thus providing a constant charging current for the condenser. The impedance of the pentode and therefore the charging current can be controlled either by variation of screen volts or control grid volts. A circuit incorporating this charging method and employing a

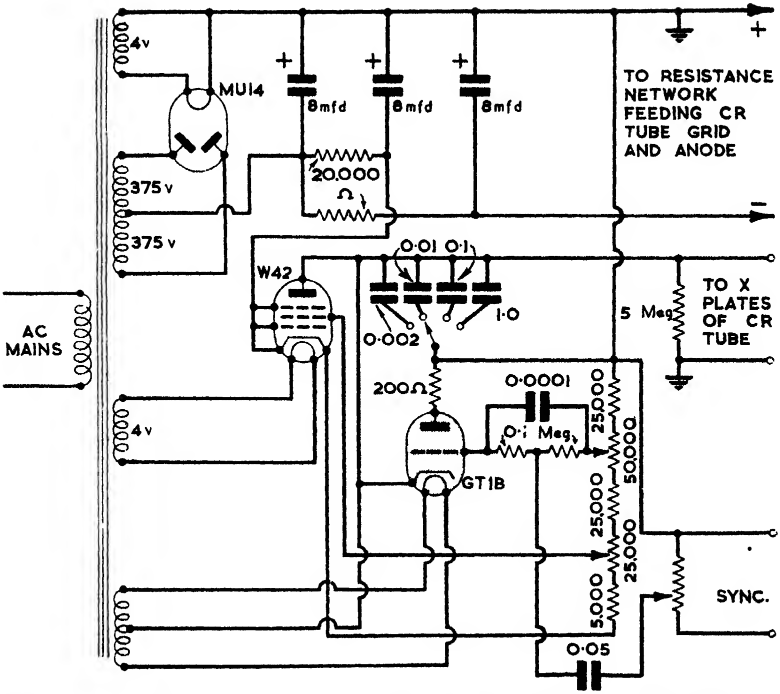


Fig. 9.—Time Base Circuit Using a Pentode as the Charging Impedance. This circuit provides a frequency range of 10 to 10,000 c.p.s.

gas-filled relay to discharge the condenser, is given in Fig. 9. This time base circuit is suitable for soft C.R. tubes and was developed by the G.E. Co., Ltd. With the circuit values given, this time base will provide a frequency range of 10 to 10,000 cycles.

The frequency of a time base is, of course, governed by the relative values of C and R. When C is expressed in microfarads and R in megohms, C × R gives us the approximate time constant of the circuit in seconds. Clearly, therefore, an indefinite number of changes may be rung on the values of C and R to give us the same time base frequency. In practice, the value of C is governed by the fact that excessive current flows through the relay if C is too large, while there is a tendency to oscillation if C is very small.

In Fig. 9, C is variable by means of a tapping switch and R has been replaced by the impedance of the pentode which is

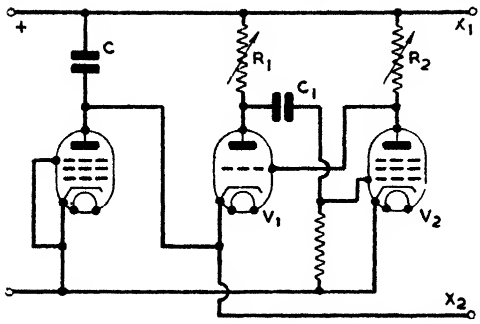


FIG 10 ILLUSTRATING THE PRINCIPLE OF THE PUCKLE HARD VALVE TIME BASE CIRCUIT

similarly variable by changes of potential on the control grid or screen grid When CR is large the resultant sweep frequency is low Using, for example, the 1 0 mfd tapping in Fig 9 for the charging condenser C, the impedance of the pentode would be of the order of 100,000 ohms to produce a sweep frequency of 10 c p s The time base frequency can be calculated for most practical purposes from the formula

$$f = \frac{I}{CE}$$

where I is the current feeding into the condenser measured in microamps , C is the charging capacity in microfarads, and E is the difference between the striking and extinction potentials of the relay, measured in volts

Hard Valve Time Base Circuits

Each development is inevitably superseded in its turn and although the gas-filled relay still has an important part to play in modern practice, time bases incorporating them are unsuitable for very high frequencies. A hard valve time base, devised by O S Puckle, overcomes these drawbacks and is suitable for use up to frequencies of one megacycle. This circuit, which is shown in Fig. 10, has several interesting features.

The charging circuit is of the pentode type already discussed, but the triode V_1 is shunted across C and the grid of V_1 is connected to the anode circuit of V_2. When the circuit is switched on, the current flow in R_2 produces a voltage drop which biases V_1 to the point when no anode current flows. As the voltage across C builds up, however, the point is reached when anode

current begins to flow in V_1, producing a voltage drop across R_1 which is used to bias V_2. This bias has the effect of reducing the current through V_2 and therefore reduces the voltage drop across R_2 which in its turn means that the bias is reduced on V_1. In this way, the condenser C is allowed to discharge through V_1 and the discharge continues until there is no P.D. across V_1. The cycle then starts all over again. R_2 controls the sweep volts available and R_1 the flyback time. Frequency, as before, is governed by the amount of current flowing through the charging pentode and the value of C.

Synchronising

In practical use, the time base circuits we have discussed would be quite satisfactory with the exception that there would probably be a tendency for the image under observation to wander. This is obviated by synchronising which is simply a means of keeping the time base sweep frequency at a fixed value relative to the phenomenon under observation. The practical means adopted to keep the two in step is to tap off a little of the " work " voltage and use it to trip the time base circuit. One method of introducing the synchronising voltage is included in the circuit of Fig. 9.

Symmetrical Deflection

With high vacuum C.R. tubes, there is a tendency for the spot to lose focus at the extremities of its swing. This is caused by the de-focusing effect exerted by the potential on the deflector plates and it naturally increases as the beam approaches one or the other of each pair of plates. To avoid this trouble, symmetrical deflection is adopted. Under this arrangement, the plates are joined together through suitable values of resistance and the electrical centre of the junction is maintained at the potential of the final anode—or, in other words, the plates are connected to the final anode as shown in Fig. 11.

The time base circuit has now to be modified so as to deliver a symmetrical output which is achieved by providing a push-pull output stage. The hard valve time base circuit, already discussed, can be made to deliver the required output by the addition of a further triode connected as shown in Fig. 12. In this circuit, developed by Cossors, the charging condenser

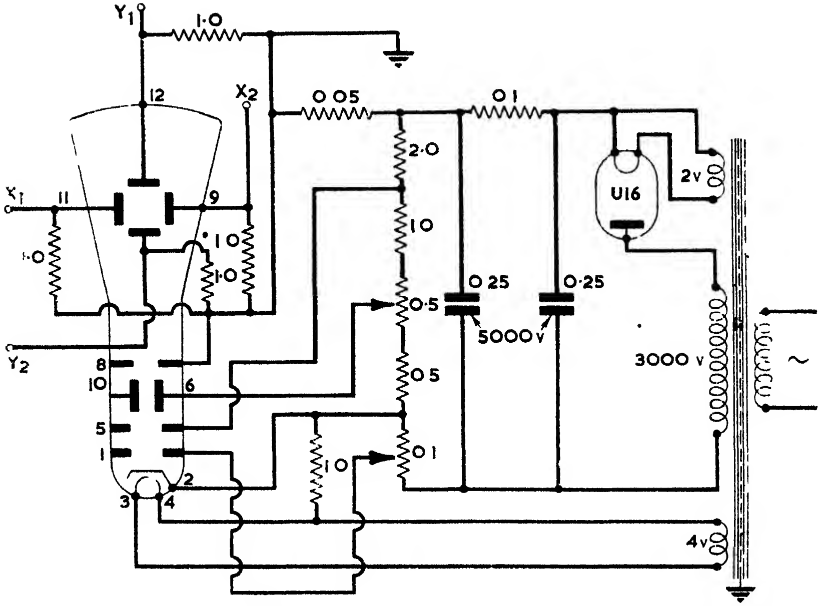


FIG. 11.—H T. SUPPLY CIRCUIT FOR C.R. TUBE DESIGNED TO PROVIDE AN OUTPUT OF 4,000 VOLTS

consists of two parts, C and C_1, the value of C being determined by dividing C_1 by the stage gain of the valve $\left(C = \frac{C_1}{\text{Gain}}\right)$. One of the C.R. tube plates is fed direct from C, while the other plate is fed through the valve so that X_1 and X_2 are always in phase opposition, which is the required output.

In addition to overcoming the de-focusing trouble, symmetrical deflection affords the further advantage of requiring only half the deflection volts to provide the same swing as is obtained from a straight circuit.

Hard C.R. Tubes

The gas-filled C.R. tube makes use of ionization by collision to assist focusing of the ray. This is a simple and effective method for low-frequency work, but the gas-filled tube has largely given place to the vacuum type for modern use. These hard tubes usually operate at far higher potentials than the gas-filled types and incorporate additional anodes or accelerators to assist focusing. In the double or triple accelerator type of C.R.

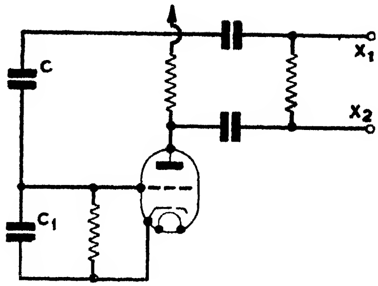


Fig. 12.—Method of Obtaining Push-Pull Deflection

tube, the Wehnelt cylinder is still adopted but does not play the important part in focusing that it does in the gas-filled tube. The arrangement of the electrodes and the potentials applied are so designed as to produce electrostatic fields which form "electron lenses" acting on the electron beam in the same manner as optical lenses focus a ray of light.

The accelerator potentials are normally progressively increasing although in some designs the first and third anodes are strapped internally. In the Cossor 11-inch high vacuum tube, for example, there are three anodes the normal potentials of which are 3,000 volts, 1,500 volts and 3,000 volts respectively.

Electromagnetic Deflection

Magnetic means of focusing and deflection are now commonly adopted for television reproduction. Some types provide a 15-inch diameter screen and all are hard tubes. These tubes have only one anode and are, therefore, similar in construction to the gas-filled tube, but do not incorporate any deflecting plates inside the neck of the tube. A focusing coil is arranged around the neck of the tube to assist concentration of the electron beam to a fine spot on the screen and deflection of the beam is achieved by mounting two pairs of coils mutually at right angles, in a similar position to that which the deflecting plates would normally occupy, but outside the tube.

Fluorescent Screen Materials

Materials possessing the property of fluorescing under the impact of electrons differ both in the colour of fluorescence and its duration. Some materials have a long after-glow amounting

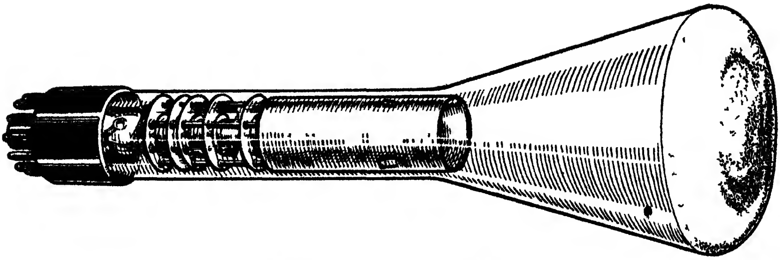


FIG 13.—COSSOR DOUBLE BEAM TUBE.
Externally this C.R. tube does not differ appreciably in appearance from the normal type.

to several seconds, while others are almost immediately extinguished when the spot changes its position. Each type has its proper place, a long after-glow being necessary, for instance, in the analysis of transient or very low-frequency phenomena such as are encountered in cardiography. On the other hand, negligible after-glow is permissible for very high-frequency work such as television demands.

The table below gives the principal screen materials, the colour they provide and the duration of after-glow :—

Material.	*Colour.*	*Afterglow.*
Cadmium Tungstate ..	Blue	8 Microseconds.
Calcium Tungstate ..	Blue	8 ,,
Zinc Silicate (Willemite) ..	Green	5 Milliseconds.
Zinc Sulphide	White	Nil.

Very small changes in the formulation of screen materials, or the addition of impurities, can make an extremely marked difference to the characteristics of the screen both in colour and duration of after-glow.

Double Beam C.R. Tubes

The single beam C.R. tube, as we have seen, can be deflected in two planes simultaneously, but it is not possible with the single beam to examine two independent phenomena simultaneously in relation to time, as is possible with electromagnetic oscillographs. To enable this object to be achieved with the C.R. tube, the remarkable technical device has been adopted of splitting the beam into two rays which are electrically in phase, but spatially 180 degrees out of phase. The X plates are common to

both beams, so that where a linear time base is employed, the time scale obtained is also common to both beams. Each Y plate, however, controls only one of the beams so that two different variables may be applied to the Y plates enabling two different traces to appear on the screen, but utilizing a common time base. It would be possible, for example, with this double beam tube to examine the voltage and current curves of a circuit simultaneously. The method of splitting the beam is to introduce an additional plate between the Y plates. This can clearly be seen in the illustration of the electrode system of a Cossor double beam tube.

High Voltage Tubes

By radio receiver standards, even the low and medium voltage cathode-ray tubes require extremely high anode potentials ranging between 500 and 5,000 volts. Some types of tube used for laboratory purposes require anode voltages in excess of 50 kilovolts, but it is unlikely that these will be encountered in everyday radio practice. Another application for a special type of high voltage tube is for the projection of television images on to a screen.

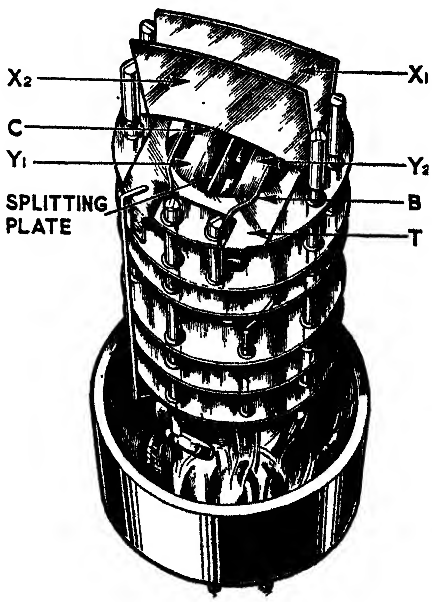


FIG. 14.—INTERIOR OF DOUBLE BEAM C.R. TUBE.

The illustration shows a close-up view of the electrodes. The X plates are common to both beams but each Y plate controls one beam only. The beam separation is achieved by the introduction of the splitting plate between the Y plates

Features of Commercial Tubes

Miniature tubes have much to recommend them for radio work. The 1½-inch screen G.E.C. tube is intended for use in portable oscillographs of the type used for radio servicing. The tube measures only some six inches in length and operates at relatively low voltages. All four deflector plates are brought out to separate pins so that push-pull deflection can be adopted. The tube may be operated with an asymmetrical time base, but the results will be less satisfactory.

Indirectly heated cathodes are virtually standard practice and in some tubes there is a separate cathode connection which allows modulating voltages to be applied between cathode and grid without risk of the distortion that may otherwise be caused by the capacity to earth of the heater transformer.

In electromagnetic tubes the position of the focusing coil which acts as a lens depends upon the size of the spot required. Moving the focusing coil closer to the grid aperture will increase the diameter of the spot and will also increase the ampere turns required for focusing. The converse is true when the focusing coil is moved away from the grid aperture.

Power Supplies.

In general, all-mains operation is desirable for C.R. tubes and some variation may be encountered in the recommended methods of obtaining supplies from an A.C. source. In some instances, it is recommended that a separate transformer be employed for providing the heater supply to reduce the risk of breakdown of insulation in the H.T. transformer. In normal practice, little difficulty will be experienced if a common transformer serves for both heater and high voltage supplies.

A circuit capable of providing 4,000-volts between cathode and final anode is given in Fig. 11. This is a straightforward half-wave rectifier circuit with resistance smoothing. The requisite potentials for the various electrodes are obtained by tapping off at appropriate points down the resistance network. Allowance is made for variable control of the potentials applied to the grid and first anode.

If troubles are experienced due to interaction arising from the feeding of all electrodes from a common H.T. supply, decoupling condensers may be connected across the resistances forming the potential divider.

Practical Points on the Use of Tubes

A code of practice governing the use of C.R. tubes in equipment is included in B.S.1147, 1943. It provides many useful reminders on the treatment which should be accorded the C.R. tube to ensure maximum life and efficiency.

It is strongly recommended that rigidly fixed sockets should be avoided in the mounting of C.R. tubes, because rigid fixing may cause severe mechanical stresses between the base and the tube. The fixing should be resilient and, with horizontal mounting, the correct method is to support the tube at a point near the maximum diameter of the bulb. A light fixing is required for the neck near, but not actually on, the base. Another point requiring watching when laying out equipment employing C R. tubes is to ensure that adequate ventilation is provided.

In a high vacuum tube, particularly one of large diameter, the glass walls are obviously subjected to considerable pressure from the atmosphere. Care must, therefore, be taken to avoid mechanical shock or scratching the surface of the glass since even slight marking may seriously weaken the bulb. Reasonable care must also be taken of the screen to ensure a long tube life. If a high intensity spot is allowed to remain in any one place for any length of time the screen will be damaged. Where it is necessary for the spot to remain stationary the beam current must be reduced to a minimum.

Where cathode earthing is adopted in a C.R. tube, the whole trace may shift bodily when an earthed body is brought close to the screen. For accurate work it is desirable to earth the final anode, but when all precautions of this type have been taken, it must always be recognized that results will be seriously affected by stray magnetic fields. In uses where such fields are likely to be introduced by adjacent components, the effects can be minimized by shrouding the tube with a shield of high magnetic permeability.

Applications.

The C.R. tube has become a standard piece of laboratory equipment and is invaluable for electrical measurements of all types, for radio servicing and for monitoring purposes, such as in radio broadcasting stations. Its widespread use in television receivers, too, will eventually take it into almost every home.

Treated with care and respect, the tube does not present many problems in normal operation. But by everyday standards, however, all C.R. tubes are high voltage equipment and this fact must always be borne in mind in the design of apparatus incorporating C.R. tubes as well as in their operation and servicing.

CHAPTER XXIII

PHOTO-ELECTRIC CELLS

THE various electrical phenomena which are caused under certain conditions by the action of light have long been known to scientists, but it is only during fairly recent years that these discoveries have been applied to practical uses. This development was made possible by the gradual evolution of devices embodying the different effects in a form which permitted their direct application to a variety of uses. These devices, which differ from each other according to the particular effect employed, are known as photo-electric cells or photocells.

There are four different photo-electric effects, each corresponding to a different form of photocell; the classification being as follows:

1. *Photo-electric emission,* in which electrons are ejected from specially prepared metal surfaces by the action of light. The *emission type photocell* utilising the effect contains the sensitive surface and an electrode for collecting the electrons within an evacuated or gasfilled glass envelope. The current produced is measured in microamperes, and an amplifier is required in the majority of applications.

2. *Photo-conductivity,* in which a change of resistance takes place in a thin film of selenium when the illumination varies. The effect is utilised in the *photo-conductive* cell, also called the selenium cell or selenium bridge, to operate auxiliary devices such as relays either directly or through the medium of an amplifier, according to the application.

3. *The Photovoltaic* effect, in which illumination of the region of contact between two specially prepared conducting surfaces causes a flow of current between the respective materials. Owing to the rectifying properties of the contact the current flow is in a particular direction. The *photovoltaic cell* or rectifier type photocell which utilizes the effect generally produces a

current of a few milliamperes and may be used with or without an amplifier.

4. *The Becquerel effect,* in which the illumination of a cell containing two special electrodes immersed in a liquid electrolyte produces at the terminals a small voltage. The arrangement utilising the effect is called a *Becquerel cell,* after its discoverer, or a photo-electrolytic cell.

There has been a great deal of confusion in the terms used to distinguish the various photo-electric effects and types of cell, but the foregoing terms are in general use and seem satisfactory for the purpose of general description.

PHOTO-ELECTRICITY

It is among the most remarkable discoveries of science that, under suitable conditions, an electric current in the form of a stream of electrons may be drawn from a metal merely by allowing light to fall upon it. Like so many other important discoveries it was largely accidental, and arose out of experiments carried out by Hertz in 1887, when it was found that a negatively charged body lost its charge rapidly when subjected to the action of light, particularly the light of short wavelength from the ultraviolet region of the spectrum. Positively charged bodies did not show the effect.

We now know that a negative charge is simply an accumulation of electrons, so that the loss of negative charge in the experiment means that the electrons representing the charge are driven from the body by the action of light falling on its surface. At the time of the discovery, however, the idea of electrons had not yet appeared, and no reasonable explanation of the effect could be given. (The principles of photo-electric emission are dealt with in Chapter II. See page 53).

Photo-electric Materials

It was soon found that a particular group of metals, the alkali metals, gave a strong photo-electric effect with light corresponding to the visible part of the spectrum. The metals in question are very active chemically, and the technique of manufacture of photocells employing them is a highly specialized one calling

for the greatest chemical purity of component materials, very high degrees of vacuum, and absence of any form of contamination. Particulars of the principal alkali metals are given in the following table :

Metal.	Chemical Symbol	Melting Point, °C.	Density, grams per cubic cm.	Work Function, Volts.	Threshold Wave-length, Angstrom units. (10^{-8} cm.)
Barium ..	Ba	850	3·78	1·7	7,300
Caesium ..	Cs	26	1·87	1·36	9,110
Lithium ..	Li	186	0·534	2·36	5,250
Potassium ..	K	62·3	0·870	1·55	8,000
Rubidium ..	Rb	38·5	1·53	1·45	8,550
Sodium ..	Na	97·5	0·970	1·82	6,810
Strontium ..	Sr	800	2·60	2·0	6,200

The work function is an index of the degree of difficulty with which electrons are ejected ; the metals with the lowest work functions being the most efficient photo-electric emitters. It is seen that caesium has the best performance in this respect, and as its reponse to light of different wavelengths is similar to that of the human eye it is widely used in emission photocells.

The threshold wavelength referred to in the table is the maximum wavelength of the incident light which will give any observable photo-electric emission. As the wavelength is the inverse of the frequency, this is the same as saying that the light must have a frequency exceeding a definite minimum, called the threshold frequency, before it can liberate electrons. With any given substance, light of a colour corresponding to a frequency below the threshold value can fall on the substance indefinitely without producing a single electron.

The Effect of Light Colour

The current produced by an emission type photocell is proportional to the intensity of the light, provided that the colour of the light remains constant. If the colour varies with a given intensity the emission also varies. The relationship between

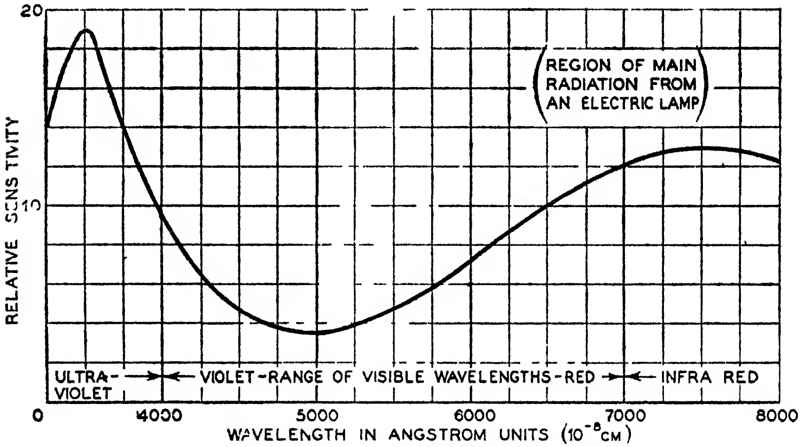


FIG 1.—SPECTRAL RESPONSE CURVE OF CAESIUM PHOTOCELL
(*B T H Co, Ltd*)

the emission and the colour of the light (usually expressed as wavelength) is called the *spectral response* and depends upon the material used for the sensitive surface. Each material has a different response to colour, and it is usual for a spectral response curve to be given by the manufacturer for each type of cell. The curve corresponding to a typical caesium cell is shown in Fig. 1, from which it is seen that a region of maximum sensitivity occurs with light from the infra-red part of the spectrum. Caesium gives a good response with all visible colours of light, and is, therefore, well suited for use with gas-filled electric lamps and for purposes of colour comparison.

The sensitivity of a photocell is expressed in microamperes per lumen, care being taken to specify the colour of the light employed. It is usual to take this as corresponding to an electric lamp with its filament operating at a definite temperature, generally in the region of 2,500 degrees Centigrade. The *lumen* is the unit of luminous flux or quantity of light and is the amount of light falling on a surface of one square foot located at a distance of one foot from a source having an intensity of one candle-power. The inverse square law applies to illumination, so that if the distance from the source is doubled, for example, the quantity of illumination is reduced to one fourth of its original value.

Types of Cell

In general, the emission photocell consists of a plain electrode covered with a thin film of one or other of the alkali metals and sensitized by a special process to obtain the maximum photo-electric response in terms of the current produced with a given intensity of illumination. This electrode is either flat, or shaped to catch the maximum amount of light, and forms the cathode. It is faced by the anode, which usually takes the form of a wire loop so as to obstruct as little as possible the light directed on to the cathode. Both electrodes are arranged for external connection, and are enclosed in a glass bulb as shown in Fig. 2, representing a typical construction. For special purposes there are sometimes radical departures from this simple type; the anode may take the form of a wire gauze cylinder surrounding the cathode, and in some cases the sensitive anode surface is deposited as a film on the inside walls of the bulb, in which case a window is provided for admitting light. In all cases, the anode is made positive with respect to the sensitive cathode so as to attract and collect the emitted electrons.

Vacuum and Gas-filled Cells

There are two essentially different types of cell, according to whether or not a gas filling is used in the bulb. In either case the bulb is highly exhausted, but in the gas-filled cell a small amount of inert gas, such as argon, is introduced after the evacuation process. The presence of this gas alters the relationship between the output current and the amount of light falling on the cathode, and gives a high sensitivity, *i.e.*, a high current for a given illumination.

The difference between the two types is shown by the curves in Fig. 3, where current output is plotted against applied voltage for a fixed value of illumination. Curve 1

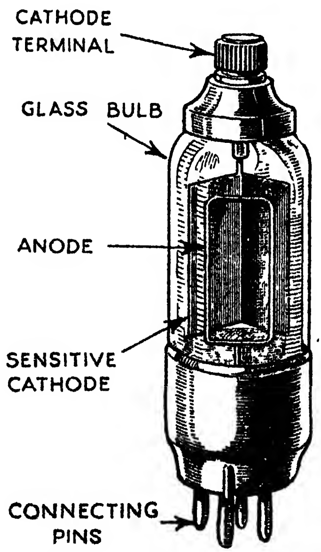


FIG. 2.—TYPICAL EMISSION TYPE PHOTOCELL.
(General Electric Co., Ltd.)

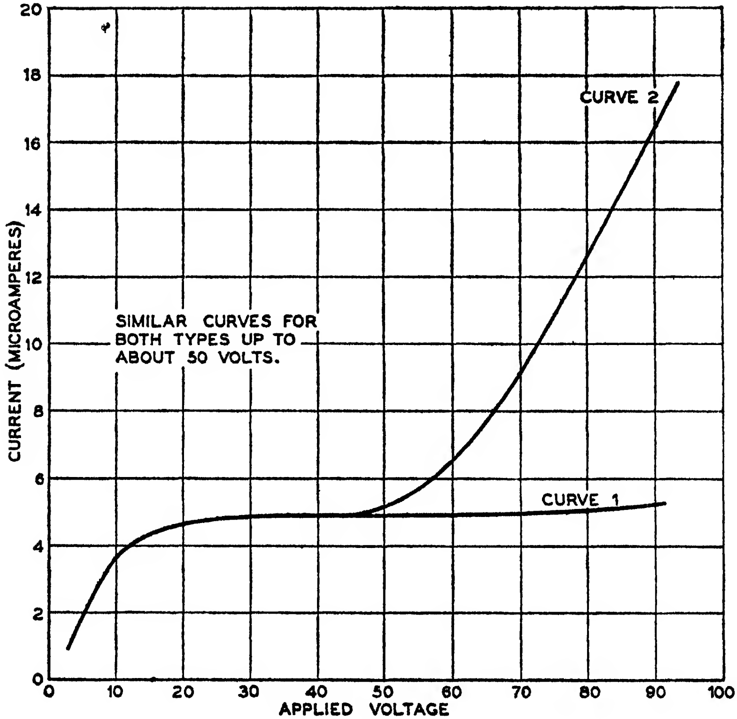
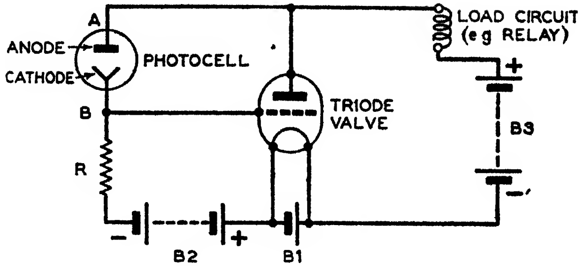


FIG 3—RELATION BETWEEN VOLTAGE AND OUTPUT CURRENT
Curve 1 is for vacuum and curve 2 for gas-filled photocells

applies to the vacuum cell, in which the current reaches a constant or saturation value in the region of about 20 volts. In the gas-filled cell, represented by curve 2, the same general features are retained at low voltages but at about the region of 50 volts an increase in voltage is accompanied by an increasingly sharp rise in current, the increase being due to the ionization of the discharge path caused by the collisions between electrons and gas molecules.

In practice the current must be limited, as by means of external resistance, or the cell may be seriously damaged if an excessive current flows. Although the increased sensitivity of the gas-filled cell enables it to detect lower values of illumination it is not so stable as the vacuum cell, which is preferable where measurement of illumination as distinct from detection is required.

FIG 4
SIMPLE FORM OF AMPLIFIER CIRCUIT FOR USE WITH EMISSION TYPE PHOTOCELL (ON-AND-OFF CONTROL)



Valve Amplification

As the current output of an emission type photocell is only a few microamperes it is essential for most purposes to amplify the current very considerably before any practical purpose can be attained. It is here that the thermionic valve enables the emission photocell to be used in a wide variety of applications by multiplying its feeble current changes and following these changes without time lag. The speed of response of an emission cell is very high, especially for the vacuum type, in which the current follows the illumination within much less than a millionth of a second. With a gas-filled cell a certain amount of time lag is introduced by the fact that time is required for the ionization process, but it is only at high frequencies of operation that the time lag becomes noticeable. In either case the added lag due to the amplifying valve is altogether negligible for all ordinary purposes.

The simple circuit in Fig. 4 illustrates the basic principles of valve amplification. Assuming that the cell is dark, no current flows between A and B and the valve is biased practically to the cut-off point by battery B2 through resistance R so that its anode current is zero or some small value which will not affect the relay. Illumination of the photocell causes electrons to flow from cathode to anode and the resulting current which passes through resistance R causes point B (corresponding to the valve grid) to become less negative. This reduction of grid voltage causes the valve to pass anode current provided by battery B3, so as to operate the relay. This is a very simple form of application showing how variations of photocell current may be used to produce variations of the very much greater anode current provided by a thermionic valve. In contrast to simple "trigger" or on-and-off applications of this kind the emission photocell is

used in such applications as the sound film and television as a means of controlling a valve so that its anode current variations are a true reproduction of extremely rapid changes of illumination.

Electron Multipliers

In cases where the output from a photocell must be greatly increased before it can be put to its intended use, there may be considerable difficulty in applying a valve amplifier for this purpose. When several stages of amplification are necessary troubles arise from several sources, including microphonic noise in valves, variable leakage effects and the pick-up of spurious signals. The resulting distortions are amplified along with the proper signal, which tends to become lost against the background of random noise. In technical terms, the signal-to-noise ratio is said to be low, and this is a serious matter in such applications as television where the purest possible amplification of very weak light signals is required.

Difficulties of this kind may be largely overcome by using the electron multiplier, in which photo-electric and secondary emission effects are utilized within one envelope to produce a current several thousands of times greater than that corresponding to the photoelectric effect of the light signal received. (The principles of secondary emission are dealt with in Chapter II. See page 54.)

The principle is shown in Fig. 5, where the direction of the incoming light on to the photo-electric surface S is indicated by the dotted line. The electrons ejected from this surface are directed on to target T1, which has a suitable positive potential with respect to S. Each electron striking the sensitized surface of T1 produces several new electrons by secondary emission and this increased flow of electrons is directed towards target T2, which has a suitable

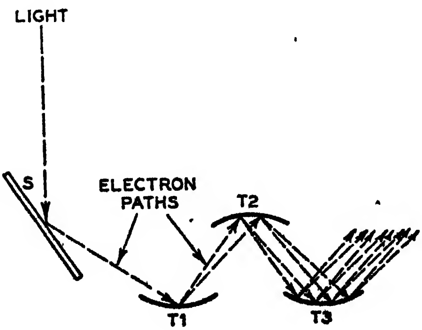


Fig. 5.

Principle of Electron Multiplier. Showing cumulative effect of 3 targets liberating 2 electrons for each electron received.

positive potential with respect to T1. The secondary emission process is repeated at T2, and a doubly magnified stream of electrons is aimed at the next target, T3. Theoretically, the multiplication can go on indefinitely, but in practice the repulsion between individual electrons causes a progressive spreading of the beams and places a limit on the number of stages used. A limit is also set by the heating of the final target anode. Magnifications of about 10,000 represent normal practice.

There are several ways of directing the electrons from one target to another. Electric and magnetic fields, or a combination of both have been used. It will be understood that as each target must be positive with respect to the one before it, the respective targets must be at increasingly higher positive potentials with respect to the photo-electric cathode. As the voltage for each stage must be of the order of 100 in order to secure the high electron velocities necessary for secondary emission it follows that considerable voltages are required for operating the arrangement.

PHOTOCONDUCTIVITY

The element selenium has been known to chemists for more than a century, but its peculiar electrical properties were unknown until the accidental discovery in 1873 that the resistance was reduced when light fell upon it.

As selenium has several chemical forms, it is always necessary to know which kind is meant when discussing its properties. It is only the grey crystalline form which is a conductor (though a very poor one) and sensitive to light. Some of its physical properties are given in the following table :—

Density (grams per cm. cube)	4·8
Melting point °(C.)	220
Boiling point (°C.)	690
Resistivity (ohms per cm. cube) ..	70,000
Linear expansion (per °C.)	$4{\cdot}9 \times 10^{-5}$

It may be pointed out that the resistivity is very high in relation to ordinary metallic conductors. Copper, for example, has a resistivity of 1·7 *michroms* per cm. cube. For this reason the resistance of selenium photocells is high; generally several megohms.

Construction of Selenium Bridges

The manufacture of selenium cells or bridges is highly specialized, owing to the necessity for obtaining just the right kind of film of selenium to give the best operating conditions. A modern type of cell is shown in Fig. 6, from which it will be seen that the general construction resembles that of an ordinary valve. In this case the electrodes are formed by two thin metal grids with projecting teeth fused on to a thin glass plate. The teeth are spaced so as not to touch each other and to minimize the capacitance between the electrodes. Molten selenium is applied to the surface and thermally treated so as to obtain the required crystalline structure. The film of selenium is normally only a few hundredths of a millimetre thick, so as to avoid the shunting effect of any inactive material, which would simply act as a short-circuiting resistance. The glass bulb is evacuated and then filled with an inert gas. The dark, or maximum, resistance of such cells ranges between about 0·5 and 20 megohms. The two connections are taken to two of the pins in a standard valve base.

The Use of Amplifiers

Owing to the appreciable current change obtainable with a selenium bridge, it is sometimes possible to operate instruments or sensitive relays directly without using an amplifier. In such cases the circuit arrangements are very simple, but when greater output is required an amplifier becomes necessary.

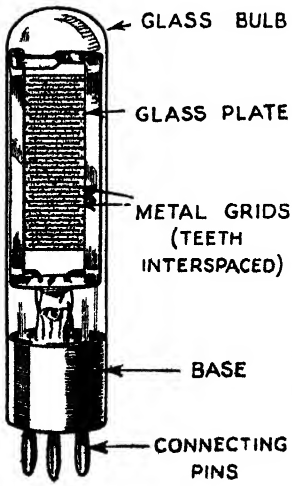


Fig. 6.
Typical Selenium Bridge.
(Radiovisor Parent Ltd).

A simple form of circuit is shown in Fig. 7, where the bridge or cell is shown as a resistance Se. With the connections arranged in this way, the voltage at the grid of the valve for a given position of the tapping on the battery B1 will be determined by the relationship between the resistances of Se and R. If it is assumed that the bridge resistance is high in relation to R then the greater proportion of the voltage will be dropped

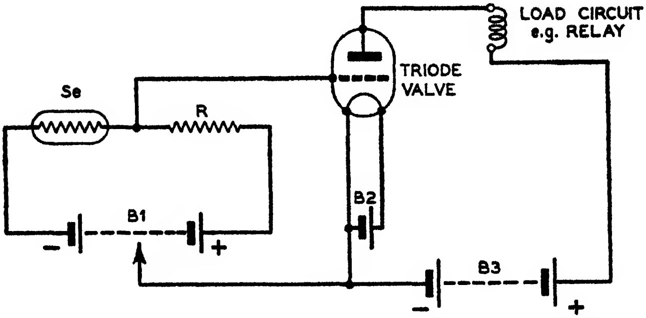


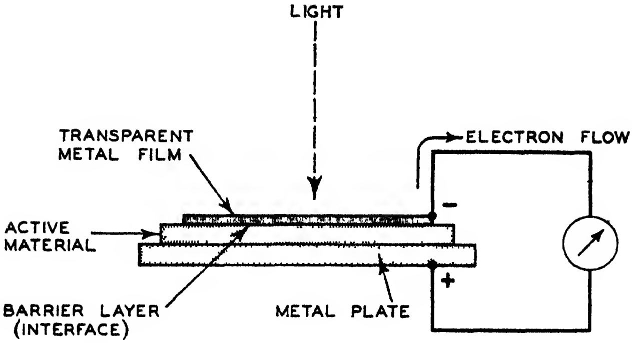
FIG. 7.—SIMPLE AMPLIFIER CIRCUIT FOR USE WITH SELENIUM BRIDGE (ON-AND-OFF CONTROL).

across the bridge. This will normally correspond to the dark condition. As the bridge becomes illuminated its resistance decreases and the voltage across it falls, while that across R increases. It can be seen that this action changes the voltage between the cathode and grid of the valve, thus controlling the anode current in accordance with changes of illumination on the selenium bridge. By suitably arranging the polarity of battery B1 and the value of R, it is possible to make the anode current of the valve either increase or decrease with increasing illumination on the bridge.

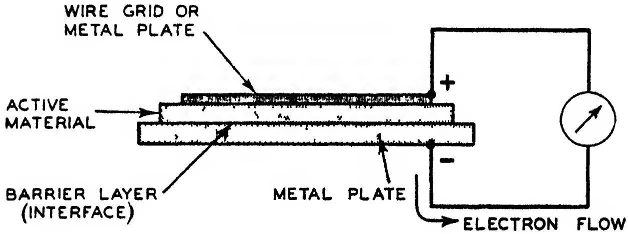
Similar principles can be applied to amplifiers working from A.C. or D.C. mains, but the arrangement naturally varies according to the application. Under conditions of rapidly varying light intensity, as in sound-film and television work, the output of selenium bridges falls off rapidly at the higher frequencies so that their use for such purposes is rather severely limited.

PHOTOVOLTAIC EFFECTS

The copper-oxide rectifier type photocell in its present form was produced about the year 1930 and was shortly followed by a similar type employing selenium. These cells differed from the emission and photoconductive types in developing a voltage when illuminated without requiring any external source of supply. This obvious advantage over the other types is, however, offset to a large extent by other features, and the use of these latest types of photocell is rather severely restricted in



(a)



(b)

FIG. 8.—ALTERNATIVE FORMS OF RECTIFIER TYPE PHOTOCELLS

(*a*) Front wall barrier layer photocell.

(*b*) Back wall barrier layer photocell.

practice to cases where simplicity of circuit arrangements is a primary consideration.

There are two ways in which the combination of materials may be arranged so as to produce the effect, as shown in Fig. 8. In the arrangement shown at (a) the active material is deposited on a metal plate (usually copper in a copper-oxide cell and iron in a selenium cell) forming one electrode. The other electrode is a very thin film of metal, so thin as to be transparent, which is sprayed on to the surface of the active material. When light falls on this transparent front electrode, its energy is able to loosen electrons in the active material in the vicinity of the interface and these electrons flow from the active material to the front electrode and through the external circuit as shewn. Just

why the electrons should behave in this manner is not easy to explain, but it is known that the resistance to their flow in the other direction is generally some thousands of times greater. This arrangement is known as a front wall cell, and the interface where the action takes place is called the *barrier layer.* A cell arranged on the principle of Fig. 8 (a) is consequently known as a front wall barrier layer photocell.

An alternative arrangement is shown at (b) in Fig. 8, and represents what is called the back wall construction. In this case the front electrode takes the form of a wire grid or a metal plate with openings for admitting light to the active material with which it is in contact. The seat of the action causing the electron flow in this type of cell is at the interface between the active material and the rear electrode so that the light has to penetrate the active material instead of only a transparent front electrode as in the case of the front wall cell. The direction of electron flow is from the active material to the rear electrode, which is accordingly negative according to convention whereas in the front wall cell it is positive because the electrons flow from the active material to the front electrode.

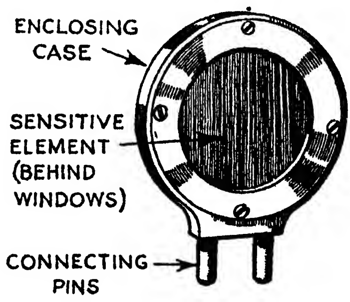


FIG. 9.—TYPICAL MOUNTING OF RECTIFIER TYPE PHOTOCELL. (*General Electric Co., Ltd.*)

Commercial types of rectifier cells are usually mounted inside a moulded case with a suitable window for admitting light, as shown in Fig. 9, but any kind of mounting may be used to suit the particular application. The elements may be either circular or rectangular, and as they do not need to operate in a vacuum they are relatively robust. With modern methods of manufacture and ageing before use the cells are very stable in operation and have a practically unlimited life.

Applications

One of the most successful uses for rectifier cells has been in portable illumination meters and exposure meters for photographic purposes.

Typical output curves for a modern wall selenium-iron cell,

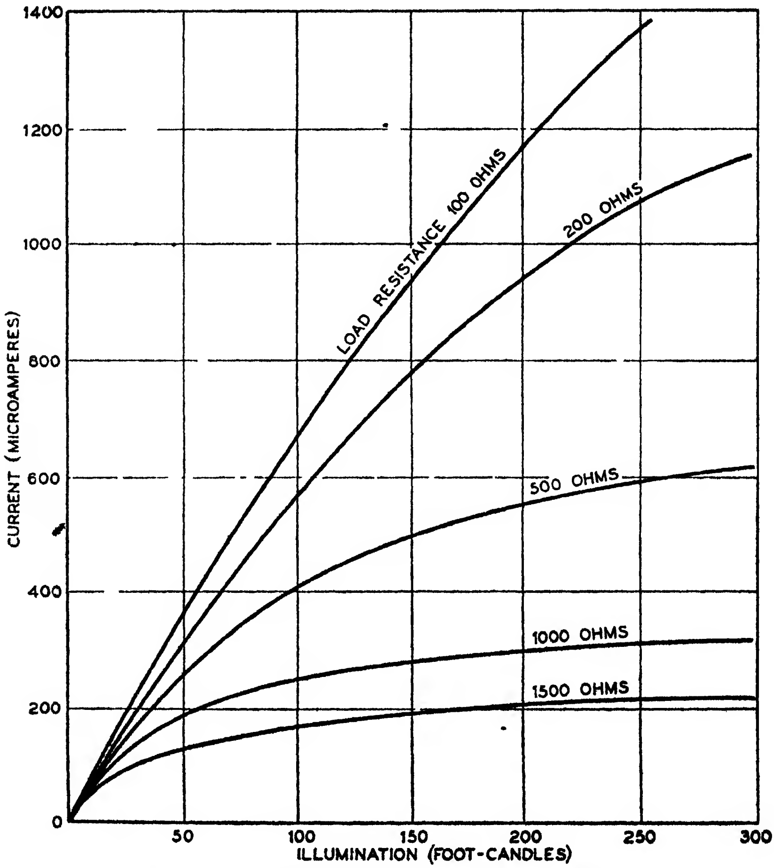


FIG. 10.—OUTPUT CURVES FOR FRONT WALL SELENIUM-IRON CELL WITH DIFFERENT VALUES OF LOAD RESISTANCE.
(*A. E. Evans & Co., Ltd.*)

showing the relationships between illumination and output current for various values of load resistance, are given in Fig. 10. With low resistances the response is almost linear, so that equal increases of illumination give almost equal increases of current over a considerable portion of the curves. This feature is of value in illumination meters and simplifies the corrections necessary when a simple current-indicating instrument is used to show the amount of illumination. The power output with a given illumination depends on the load resistance, and is a maximum when this is equal to the cell resistance. Although

the current is much greater than that obtained from an emission cell, it is not sufficient to operate a robust relay directly. The current can be increased by connecting cells in parallel, but this is not often practicable.

Use of Amplifiers

Owing to the technical difficulties in producing a reliable amplifier for use with a direct signal voltage, there are severe restrictions to the use of amplifiers with rectifier cells.

An important point arises in the use of rectifier cells owing to their construction. It will be seen from Fig. 8 that the respective surfaces between which the voltage is generated are of large area and very close together. The cell thus has considerable capacitance, the effect of which is to delay the voltage changes across the cell caused by changes of illumination. For steady or slowly varying illumination the effect is not apparent, but when the illumination is rapidly changing, as in sound-film and television work, the capacitance of the cell causes a loss of response which gets worse as the frequency of variation increases. The trouble may be overcome to some extent by making the cells as small as possible, so as to reduce the area and hence the capacitance for a given separation of the surfaces. There is evidently a limit to size reduction, and although rectifier cells for acoustical work have been made as small as 2 millimetres square it is usual to incorporate in the circuit special arrangements for increasing the output at the higher frequencies. Otherwise the high notes corresponding to these frequencies would be lost and the sound reproduction would be very imperfect.

THE BECQUEREL EFFECT

It was found many years ago by Henri Becquerel that a particular type of electrolytic cell had the curious property of producing a voltage between its terminals when illuminated. Its action is thus similar to that of rectifier type photocells, and it is indeed possible that the fundamental processes are the same.

The electrolytic or Becquerel photocell is not widely used because of its inherent disadvantages in comparison with other types and its lack of any compensating advantages. The general arrangement of the cell resembles that of a small battery with a window 'to admit light. The liquid electrolyte is generally

cuprous oxide in a solution of potassium sulphate. Light entering the window causes a one-way flow of electrons between the sensitive electrode and the electrolyte and a corresponding flow of current in the external circuit connected to the electrodes. The cell is quite sensitive in comparison with other types, but is not stable and has the rather serious defect of deteriorating with time, even when not in use.

CHAPTER XXIV

PRINCIPLES OF TELEVISION

THE transmission and reception of a moving picture is a far more complex problem than that occasioned by ordinary sound broadcasting since the eye can appreciate more than one light value simultaneously—in fact, some 200,000—consequently, if an entire picture is to be reproduced, a similar number of radio channels would be necessary unless some means is devized to circumvent this impossible requirement. In practice, the picture is broken up by the television transmitter and transmitted piecemeal, only one light value being transmitted at any particular instant; this intelligence is reassembled by the receiver and the various components of the picture are presented on the viewing screen in their correct sequence.

It might well seem that a picture recreated in this manner could not present a complete picture that would be either acceptable or realistic but fortunately the human eye has a characteristic called "persistence of vision" which enables it to retain an image for a brief instant of time after the image has ceased to exist, thus a picture built up point by point will appear to be a complete and normal picture if the repetition occurs sufficiently rapidly for the eye to retain the complete image. When the actual presentation is by means of a cathode-ray tube, persistence of vision is assisted by persistence of the fluorescent screen which remains luminous for a brief space of time after the actual cathode-ray has moved onwards.

From the foregoing general observations, it will be apparent that one of the key principles of television is the breaking down of the subject to be transmitted, and its reassembly by the receiver, a technique which is called scanning.

Before considering technical aspects of television it is perhaps advantageous to examine the broad outline of television practice

and to view the television service as a whole from the historic standpoint.

Television is far from new and experiments were in progress as early as 1884, before radio had been demonstrated as a practical possibility, early experiments using wire to conduct the electrical impulses ; even the cathode-ray tube is very much older than is generally supposed and elementary examples were manufactured at the end of the last century. One of the earliest records of the conception of cathode-ray television can be found in the proceedings of the Röntgen Society for 1911, which contains the presidential address of Campbell Swinton who reviewed the possibilities of advancement in the art of television and expressed the view that systems employing slotted discs would be found to be too crude and that the cathode-ray tube might prove to be the ultimate solution.

Television as it is understood to-day has reached a higher state of efficiency in England than anywhere else in the world ; despite the serious interruption occasioned by the late war, the ascendancy gained by this country remains unchecked.

The Transmitter

One of the chief items of interest at the transmission end is the electron camera. This truly remarkable device contains the iconoscope, on the sensitive plate of which the picture is projected by a lens and an electron beam, controlled by associated apparatus, scans this sensitive plate line by line, and in effect conveys to the transmitter the brightness of the particular point which is scanned by the electron beam at any particular instant. The movement of this beam is controlled by time base generators, one controlling horizontal movement and one vertical movement. These time bases are in turn controlled by a master synchronising device and contribute synchronising signals to the output of the transmitter so that the broadcast wave-form includes both picture and synchronising intelligence to enable the receiver to reassemble the picture in conformity with that "seen by the iconoscope." In brief, the cathode-ray beam scanning the fluorescent screen of the receiver cathode-ray tube is kept in step with the cathode-ray beam scanning the sensitive plate in the iconoscope.

The Television Receiver

Attention may now be directed to a more precise and accurate description of the functioning of the television receiver.

Although the manufacturers of modern post-war television receivers have done wonders in fitting a good deal into a small space the receiver looks, and is, a fairly large and complicated piece of equipment. However, like many other complicated things, it can be analysed and split up into its various simpler component parts. When we do this we find that it can be thought of as consisting of about six main units, which are as follows :

1. The cathode-ray tube, at the end of which is a screen on which the picture appears.
2. An electrical circuit consisting of valves and other components known as a time base generator.
3. A further electrical circuit of valves and other components for detecting and amplifying the vision signals received from the broadcasting station and then turning them into a suitable form to be applied to the cathode-ray tube.
4. A radio receiving circuit including a loudspeaker for picking up the sound transmission.
5. A power unit for transforming the power which is taken from the electric lighting mains of the house to suitable different voltages for working the whole set.
6. Although not actually part of the receiving set, an aerial and a connecting cable is required for picking up signals sent by the broadcasting station.

The Cathode-ray Tube

The cathode-ray tube is described in detail in Chapter XXII, but it is well to refresh the memory by recalling some of the details. Although it is called a tube, the cathode-ray tube is really cone-shaped, and it is on the circular base of this cone that the televised picture appears. The tube is normally mounted on the television receiver in such a way that the base of the cone is viewed directly. This part of the cone is known as the screen, and it is coated with fluorescent material. By this we mean that it is coated with a material which glows when it is suitably excited, in this instance, by the beam of electrons which are emitted by the cathode at the other end of the tube.

As we concentrate the beam in a certain direction, it is evident that we shall produce only a spot on the screen where the electron beam actually strikes it. This spot is very small (on the usual size of television screen its area would be about $\frac{1}{32}$nd in. sq. or less). The cathode-ray beam, however, can be directed to any portion of the fluorescent screen, and if the spot is so controlled a solid rectangle of suitable proportions can be formed on the base of the tube. By varying the intensity of illumination of the spot and its position in conformity with the scanning beam at the transmitter, a picture will be formed on the screen. It is interesting to note that with a picture 12 inches wide the cathode-ray beam will travel at 14,000 miles per hour.

Scanning

To produce a solid rectangle we must have a means of moving the spot both across the screen and vertically up and down. This is called " scanning " and the fundamental meaning of the word is a systematic exploration of a picture by a small spot in such a way that complete and even coverage is obtained and there are doubtless various ways in which this could be accomplished, the exploring spot for example *might* start in the centre of the picture and work outwards in a spiral. In the present system, however, the spot starts in the top left-hand corner and proceeds in a straight line to the right-hand edge and then returns to the left-hand edge just below the starting point in the quickest possible space of time, the sequence being repeated until the bottom of the picture is reached. This process is sometimes referred to as completing the frame, or frame scan. The movement from left to right is called the line scan, the cathode-ray spot being visible and modulated to the necessary illumination as may be required to reproduce the particular picture. The rapid return from right to left is known as the fly-back and is not visible since the modulating grid of the cathode-ray tube is biased to cut-off. In these circumstances the actual beam may either have such a low density that no visible impression is made, or may be entirely absent in which case the fly-back takes the form of a readjustment of the deflecting voltage or current rather than the actual movement of a beam.

Reference to Fig. 1 will show an elementary form of scanning and is worthy of some study ; it will be seen that the visible lines are not precisely horizontal but incline downwards as they

proceed from left to right due to the frame scan which produces the second dimension of the picture; it may seem odd that the lines are not horizontal and the fly-back inclined at the angle necessary to bring the beginning of one line immediately under the beginning of the previous line, this however would be impracticable as the influence of the frame scan is continuous and since the rate of travel of the cathode-ray beam along the line is slow compared to the rate of fly-back, it follows that the influence of the frame scan will be greater during the relatively long duration of the line than the shorter duration of the fly-back.

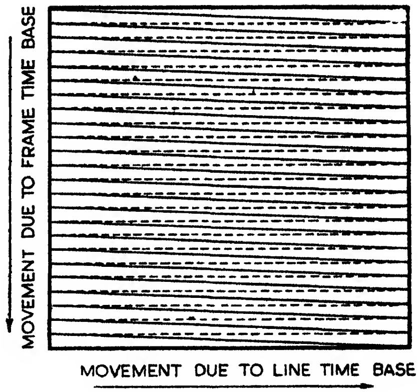


Fig. 1.—An Elementary Form of Scanning.
The solid lines represent the picture lines, the dotted lines the fly-back.

The terms line scan and frame scan have already been explained; the apparatus which generates the change of voltage or current which brings about these movements of the cathode-ray beam are known as scan generators or time bases and the actual *pattern* made by the cathode-ray beam irrespective of modulation is called the raster, a *single* complete excursion of the beam from the top left-hand corner to the bottom right-hand corner is known as a frame.

Since we want to see the picture continuously, it is necessary to trace out the whole picture on the screen completely and in such a short time that our eyes will not have forgotten what the first part of the picture looks like before we see the last part. Fortunately, the human eye will continue to hold an image which it has seen for some little time even after the picture has gone. This persistence of vision lasts for somewhere about $\frac{1}{20}$th of a second. If, therefore, we can complete the picture in $\frac{1}{20}$th of a second we see the whole picture at once and we do not realize that it has been built up from a succession of lines. Since we want to lay all these lines side by side in a space of time of less than $\frac{1}{20}$th of a second, it follows that our line scan generator must run quite fast.

In a 405 line, 25 frame television system (non-interlaced)

the picture would be completed in $\frac{1}{25}$th of a second and is produced on 405 lines. To produce all these lines in so short a space of time, it is necessary to run the line scan generator at a rate of 25 × 405, i.e. 10,125 lines per second. Each set of 405 lines is called a frame and, as stated above, the frame is completed in $\frac{1}{25}$th of a second. The frame generator must, therefore, run at 25 cycles per second. We can see then that it will be possible to build up a 405-line picture by running our line scan generator at 10,125 lines per second and our frame generator 25 cycles per second.

Interlaced Scanning

The simple form of scanning, just described and shown at Fig. 1, is not used by the B.B.C., as a slight flicker is apparent, because the area of maximum brilliance (that is to say the lines most recently scanned by the cathode-ray beam) moves down the picture too slowly, this difficulty has been overcome by the interlaced scanning system in which each alternate line is scanned followed by the intervening lines, an arrangement which gives a more even illumination over the picture area since the average illumination of any one pair of adjacent lines tends to be equal to that of any other pair. The principle of interlacing can be easily followed by a study of Fig. 2, it might well seem that the appropriate time bases would be extremely complicated but the whole problem is greatly simplified if each frame contains an odd half line.

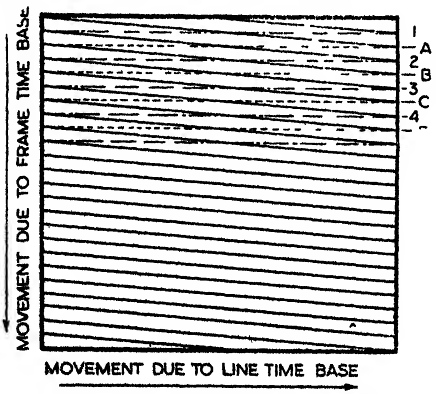


FIG. 2.—THE INTERLACED RASTER.
Lines 1, 2, 3, 4 are the odd frame. Lines A, B, C, D (shown broken) are the even frame. For clearness only a small number of lines are shown and a lesser number of fly-back lines.

In the present system there are $202\frac{1}{2}$ lines per frame and 50 frames or 25 pictures per second; it is apparent, therefore, that the line time base functions 10,125 times per second and the frame time base 50 times per second; it should not, however, be assumed that the actual picture as viewed is made up of precisely 405 lines as between 10 and 20 are

wasted during the frame fly-back which takes a zig-zag path since the line time base continues to function during the frame fly-back, see Fig.3.

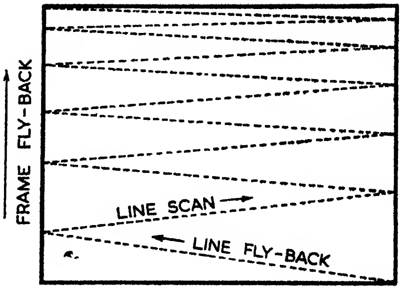


FIG. 3.—THE FRAME FLY-BACK.
Note that during this period the line time base continues to function.

In the foregoing explanation we have shown how the cathode-ray tube spot is made to trace out its pattern on the screen, and have mentioned that the actual picture is produced on the screen by modulating or varying the brightness of the spot as it traces out its lines and frames. Before saying exactly how this is done let us consider for a moment just what is meant by the brightness of the screen. On a television set the screen appears in daylight as white, or possibly slightly tinted. For television viewing, however, it is advisable to darken the room, and, of course, if the room were quite dark, the screen, in common with all other objects in the room, would be invisible, and might be said to appear black. When the spot is tracing out its pattern on the screen this will be more or less illuminated in accordance with the strength or brightness of the spot, and on every television set there is a hand control labelled BRIGHTNESS, and by turning this it is possible to make the screen either quite bright or throughout varying shades of grey to quite black, if we are viewing in the dark. Consideration of this fact shows us that if, by any means, we can vary the intensity or brightness of the spot at different points on the screen, we can obtain a pattern or picture some parts of which may be black, some white and others having intermediate gradations of grey between white and black.

Vision Channel

The part of the television receiver which is concerned with varying the brightness of the spot and so producing the picture is the vision channel. This vision channel is simply a short-wave radio receiver which, on most commercial receivers, is permanently tuned to the wavelength of the vision transmission sent from the Alexandra Palace. The circuits for this section of the receiver are known as video detectors and video ampliers

and are dealt with later in detail. The output of this receiver is applied directly to the cathode-ray tube and it varies the brightness of the spot. When the signal is strong, the spot is bright and traces out the parts of the picture which appear white. The signal varies between full strength and about one-third full strength, so that when it is one-third strength we should be producing the black parts of our picture on the screen.

At the broadcasting studios, the scene to be televized is scanned by the cameras and the broadcasting station turns the pattern of light and shade of the scene falling on the camera into a radio wave whose strength varies in accordance with the light and dark of the scene to be televized. Thus we see that we produce the movement of the spot across and up and down the screen locally, but its intensity is varied so as to form the picture by the transmission received from the broadcasting station. Since the picture is built up by varying the brightness or blackness of 405 lines, we shall not get the effect of a complete picture unless we view the screen from some distance away. If we get too close to the screen we shall see the individual lines and not the whole picture in much the same way as the old adage tells us that if we get too close to the wood we cannot see the wood for the trees.

Naturally, the technicalities and details of the circuits are fairly involved as there are numerous secondary effects which have to be taken into account. One very important feature is that we must be sure that the brightening and darkening of the spot takes place at exactly the right points on the screen so as to produce an intelligible picture in exactly the correct relative position as the original scene being transmitted. To do this we have to arrange that when the spot starts off from the left-hand side of the screen, say, there is some way of ensuring that it does so at the same moment that the camera at the transmitting studio is starting off its scanning of the actual scene to be televized. This is achieved by arranging for a small impulse, called the synchronising pulse, to be sent from the transmitter at the beginning of each line and at the beginning of each frame. The local running circuits for moving the spot are "locked" by this so that if they tend to get out of step over a period they are continually being pulled back and started off at the right moment.

This small pulse is separated out in the receiver from the rest of the transmission and applied to the scanning generator.

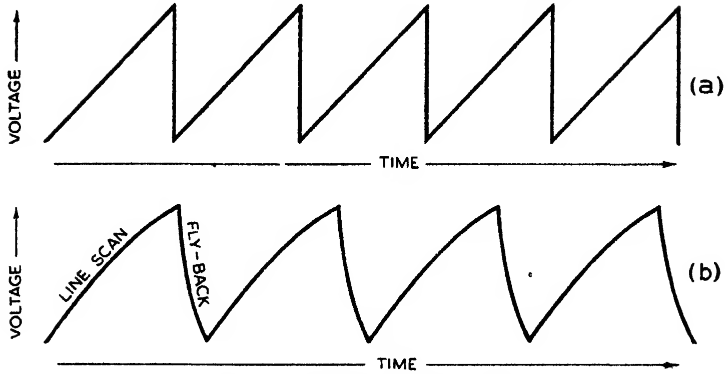


FIG. 4.—TIME-BASE WAVEFORMS.

(*a*) The waveform of an idealistic but impossible time base.
(*b*) The waveform of an acceptable time base, showing some lack of linearity in the line scan.

The Time Base

Attention can now be directed to typical time base circuits and their method of functioning, the wave-form of the perfect time base is shown at Fig. 4 (*a*) which depicts an absolutely linear line scan, that is to say the rate of voltage increase is directly proportional to time and a perfect though impossible fly-back which is accomplished in zero time. Fig. 4 (*b*) shows a more probable wave-form, a study of which will reveal that the line scan is not entirely linear and the fly-back occupies an appreciable amount of time; it is, of course, immaterial whether the fly-back is linear or otherwise.

The simplest possible form of time base is shown at Fig. 5, which although probably quite useless for any practical purpose is very suitable for demonstrating the principle. On connection to a source of supply, the capacitor C will charge through the resistor R, the potential developed across the capacitor C being led away to the deflecting plate of a cathode-ray tube. The capacitor C will not become fully charged instantaneously but will charge at a rate controlled by the resistor R. If the switch is now closed the capacitor C will discharge very quickly as the resistance of the circuit will be very low; consider now the effect of these two operations on the cathode-ray tube, when the switch is opened the voltage across the capacitor C will commence to build up and consequently the deflection plate to which it was connected will become increasingly positive and

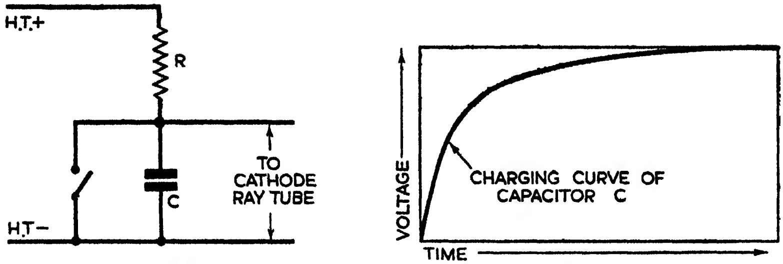


FIG. 5.—A RUDIMENTARY TIME BASE TO ILLUSTRATE THE TEXT.

the cathode-ray beam will be drawn towards it and providing the applied voltage through the resistor R is sufficiently high, the beam will be bent to such an extent that its extremity will completely traverse the fluorescent screen or any portion of it that may be desired. On closing the switch the beam will move rapidly back to its starting point and the operation may be repeated at will.

Consideration will show that the arrangement, Fig. 5, could be adapted as a television time base if the switching were dispensed with and the charge and discharge of the capacitor made automatic at exactly the right speed ; it is also desirable that the voltage difference between commencement of charge and discharge is also controllable so that the actual width of the picture may be set at some pre-determined size. Fig. 6 shows an elementary form of practical television time base but before examining this circuit in detail it will be well to establish a further point. Examination of the capacitor charging curve at Fig. 5, will show that the capacitor commences to charge quickly and this function becomes progressively slower, consequently the movement of the cathode-ray beam will not take place at a constant speed, this would result in a normal person looking unnaturally stout if appearing on one side of the picture and unnaturally thin at the other side of the picture, an undesirable feature which is known as non-linearity, in other words the curve of a time base plotted between time and voltage or current must take the form of a straight line. As will be seen later non-linearity is overcome by various means ; it would, however, be difficult if not impossible to correct such conspicuous lack of linearity as that shown at Fig. 5, it is customary, therefore, to use only a portion of the charging curve and as might reasonably be supposed, the portion selected is one which is as nearly

straight as possible, the problem of correction is then greatly simplified.

Attention may now be directed to Fig. 6 which exhibits certain of the features at Fig. 5, insofar as the resistor R and capacitor C still perform the same function and form the backbone of the circuit. The switch, however, has been replaced by a triode valve and transformer and an entirely new feature is included, the resistor R1 and capacitor C1. Inspection of this circuit will show that the resistor R, which is variable, will control the rate of charge of the capacitor C or conversely the extent to which the capacitor C can charge in a given time which controls the length of the line, since the greater the charge across the capacitor C, the longer will be the line. Since the function of the triode valve is to discharge the capacitor C, attention can now be directed to R1, C1 which play an important part. R1 is adjusted so that the grid of the valve is biased well beyond cut-off, the function of the capacitor C1 being to hold this voltage when no anode current is flowing through R1. Assuming, however, that the value of R1 is suitably chosen, the triode valve will commence to pass current when the potential across the capacitor C and consequently the voltage of the triode anode has reached a certain value, the capacitor C will then begin to discharge. It now becomes apparent that the resistor R1 will control the frequency at which the capacitor C will charge and discharge and if correctly adjusted something approaching synchronism with the transmitter can be achieved.

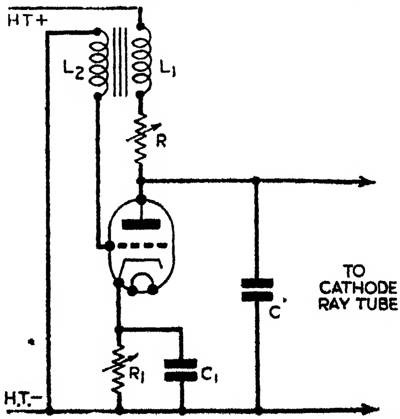


Fig. 6—The Basic Circuit of a Very Satisfactory Time Base.

Obviously, it will be impossible to maintain the necessary accuracy by manual control and some influence must be imposed by the transmitter if continuous and stable synchronism is to be obtained; the manner whereby the transmitter exerts an influence on the time base is discussed later. The point has already been established that the fly-back and consequently the discharge of the capacitor C must be relatively rapid and the action

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of the coupling L1, L2 must be taken into account. Immediately anode current commences to flow through L1 the potential developed across L2 drives the grid in the positive direction which increases the anode current which in turn drives the grid still more positive; this further increases the anode current. In other words, a snowball effect has been produced which causes an extraordinarily rapid fall in the internal impedance of the valve and corresponding increase in the rate of discharge of the capacitor C.

To summarize, the arrangement at Fig. 6, generates a slowly rising and rapidly falling potential at controllable frequency, means also existing whereby the limit of rise and fall of voltage or current can be determined. To produce the ideal time base, however, two more conditions must be fulfilled, an improvement in linearity and means whereby the transmitter can influence the precise moment at which discharge occurs.

Synchronisation and Linearity

It is perhaps more logical to deal with synchronisation before linearity since the former is a necessity and the latter a refinement. As already intimated, the transmitter wave-form includes a synchronising signal to control both the line and frame time bases the nature of which will be described later; it is sufficient for the moment to note the fact that the line synchronising signal is a pulse of short duration, compared with the frame synchronising signal, and by the selection of time constants it is possible to separate one from the other. It is the purpose of these pulses to cause the appropriate time base to commence discharging at the right moment, to act in fact as an electronic trigger.

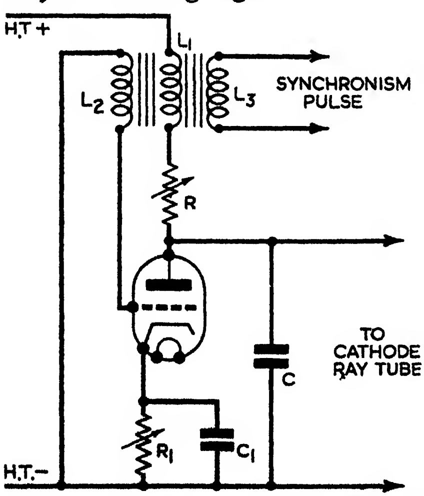


FIG. 7.—THE SAME CIRCUIT AS THAT SHOWN AT FIG. 6, BUT WITH THE ADDITION OF A TERTIARY WINDING.
This winding permits triggering by the synchronism separator valve.

It has already been explained that a time base will

discharge of its own accord and that this moment can be determined within approximate limits (in the arrangement of Fig. 6) by adjustment of the bias resistor ; it is obvious, therefore, that very little external influence is necessary to trigger it off if the time base has reached the point immediately prior to self-discharge. Fig. 7 shows Fig. 6 with the addition of a third or tertiary winding L3, the sense of which is so arranged that the arrival of the transmitter synchronising pulse will drive the grid sufficiently positive to start the flow of anode current providing that the circuit is already approaching the self-discharge point, a condition that will obtain if the grid bias is so adjusted that the time base frequency would be just slightly slower than the correct line or frame frequency, as appropriate.

The circuit, Fig. 7, constitutes a perfectly workable time base and although linearity would leave much to be desired, it is possible that it would be tolerable with minor modification if used for a small picture ; it would be more in common with general practice, however, to introduce correction. A possible modification of Fig. 7, is shown at Fig. 8 the additional valve being operated by a portion of the voltage developed across the time base capacitor C, which in the case illustrated is obtained by placing the capacitor C2 in series with C, the capacity of the former bearing such relationship to the latter that the desired fraction of the total charge voltage is obtained. It is unlikely that circuit components could be selected so that the correction of linearity is automatically satisfactory ; it is convenient, therefore, to introduce a linearity control ; one obvious means of obtaining this control would be to make the capacity of C2 variable so that the input to the corrector valve is controllable, but since a variable capacitor in this position is not particularly

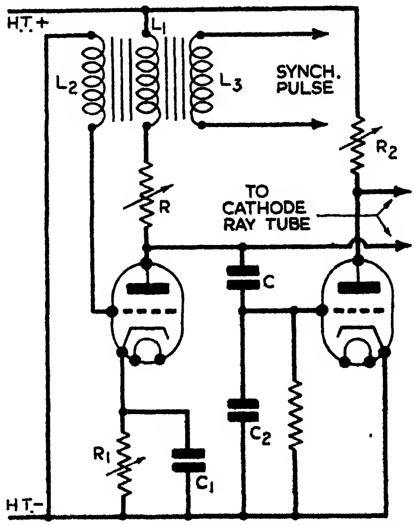


FIG. 8.—THE SAME DISCHARGE VALVE CIRCUIT AS SHOWN AT FIG. 7, BUT WITH AN ADDITIONAL VALVE TO CORRECT LINEARITY.

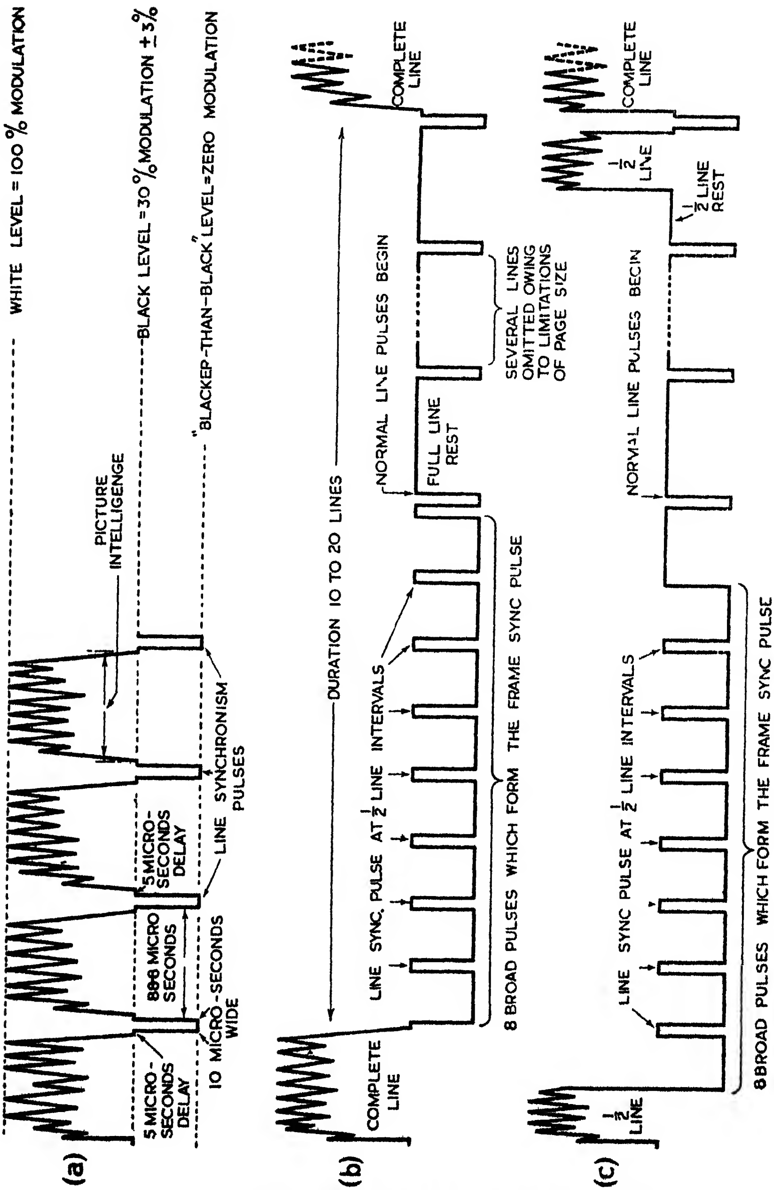


FIG. 9.—WAVE FORM OF LINE AND FRAME PULSES.
(*a*) Four lines of picture intelligence with four-line synchronism pulses.
(*b*) The waveform at the termination of an odd frame.
(*c*) The waveform at the termination of an even frame.

convenient, it is preferable to make the anode resistor R2 variable which, by controlling the anode voltage of the corrector valve, will influence the extent of its contribution to the output of the time base, permitting under-correction, over-correction and when suitably adjusted, optimum correction. Later in this chapter, a complete line and frame time base with synchronising separator is shown and further details are explained, but for its full appreciation some knowledge of the wave-form of the transmitter is necessary and attention can now be usefully turned to this subject.

Synchronising Pulses

The Alexandra Palace television transmitter differs radically from normal sound transmitters, being power modulated instead of amplitude modulated, that is to say, *when modulation is absent output is also absent*; of the total modulated power output about 30 per cent. is devoted to synchronism and about 70 per cent. to picture intelligence. Fig. 9 (*a*) shows in diagrammatic form four transmitted lines separated by line synchronism pulses. For obvious reasons the 30 per cent. modulation line is designated black, increase of modulation passing through various shades of grey, culminating in white at 100 per cent. modulation. It will also be observed that zero to 30 per cent. modulation is designated blacker-than-black; this rather imaginative terminology is favoured by the writer as it paves the way for easy explanation of the absence of synchronising pulses on the actual screen since these occur between blacker-than-black and black. This illustration also shows the duration of each line synchronism pulse; particular attention is drawn to the brief rest which occurs just before the synchronism pulse to allow the signal to return to black before its commencement and immediately afterwards to allow the receiver to "settle down" before commencing picture intelligence.

Figs. 9 (*b*) and 9 (*c*) show the termination of the even frame and odd frame respectively, and should be studied in close connection with Fig. 2. It will be seen that the duration of the frame time base is relatively considerable and that it is interrupted at half line intervals since it is necessary to keep the line time base working during the frame synchronising pulse in order that the former is not out of step at the commencement

of the new frame ; half line interruption is used instead of line interruption purely as a matter of convenience at the transmitter to simplify the commencement of the frame time base at the end of either line or half line, according to whether an even or odd frame is being terminated. The half line interruption is ignored by the line time base as it is not near enough to the self-discharge point for the intermediate synchronism pulse to trigger it.

It will be noted that at the cessation of the frame time base several complete lines without picture intelligence are transmitted before picture modulation begins.

Synchronism Separation

It has already been made clear that the line and frame synchronism pulses have to be separated from each other and to this may be added the necessity for preventing picture intelligence from accidentally triggering the time bases ; various methods of synchronism separation are possible and are the subject of continuous development but two in general use employ twin diodes and a split or twin anode pentode. It is believed that this latter arrangement was first introduced by A. C. Cossor, Ltd., who manufactured a special valve for this purpose at the inception of domestic television, known as the Cossor 41 MTS. As a matter of convenience, these two arrangements are dealt with in the order mentioned and attention is directed to Fig. 10, which shows a diode synchronism separator circuit ; the entire transmitted wave-form is fed into the circuit in such a way that a decrease in modulation drives the diode anodes in the positive direction, causing a progressive increase in anode current which increases the potential developed across the cathode load resistors R1 and R2. No deliberate capacity is associated with the load resistor R1, the top end of which is led away to the line time base. R2, on the other hand, is associated with a time constant circuit R3 and C in order that the line synchronism pulse will produce a voltage change that is small enough to be ignored whereas the frame synchronism pulse, which is of longer duration, will trigger the frame time base.

The resistor R4 and the capacitor C2 in Fig. 10, have relatively high values, say 0·5 megohm and 0·25 mfd. and produce a standing

bias on the valve so that the increase of positive voltage on the diode anode caused by the change from 100 per cent. modulation to 30 per cent. modulation, does not result in the flow of anode current, but further change from 30 per cent. to zero brings about the desired rise in anode current; thus during the transmission of picture intelligence the diode is inoperative, but becomes operative on the leading edge of the synchronism pulse. Clearly the values of R4, C1 must be chosen with care and, in practice, it is better that R4 is variable.

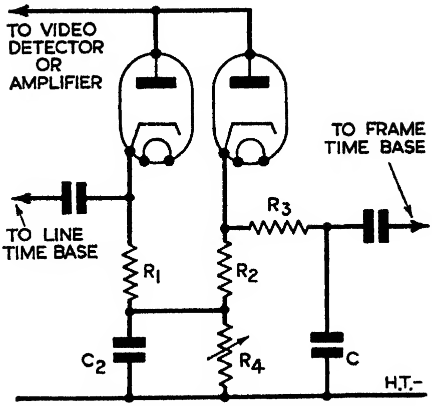


FIG. 10.—SYNCHRONISM SEPARATOR CIRCUIT USING DIODES.
Note the time constant circuit R3 and C.

If it is desired that the average user should make adjustment, it is preferable to make only a portion of R4 variable and the remainder fixed or preset. The standing bias across R4 may be as much as 50 volts, the diode or diodes selected should, therefore, be capable of withstanding this voltage difference between cathode and heater, a requirement which is not met by every valve of this type. It will be observed that connection to the line and frame time base is effected through a capacitor in order that the time base discharge valve circuits will not reduce the standing bias across R4 or be affected by it; this type of synchronism separator is, perhaps, to be preferred when triggering is effected by direct connection to the discharge valve grid circuits as the output voltage may be high, but output current relatively small. When triggering is to be effected by a change in current as in Fig. 8, the split anode pentode synchronism separator has much to recommend it.

Fig. 11 shows the basic circuit of the split-anode pentode synchronism separator; the arrangement is simple and automatically achieves freedom from unwanted coupling between line and frame time bases. Synchronism control is most conveniently achieved by making the resistor R partly variable or preset, and like the resistor R4, in Fig. 10, it provides a standing bias so that the valve is inoperative during the transmission of

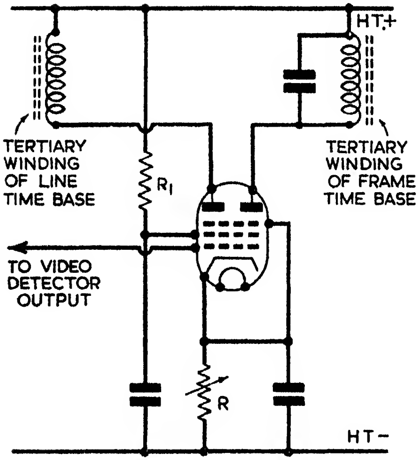


FIG 11.—THE SPLIT ANODE PENTODE SYNCHRONISM SEPARATOR DESCRIBED IN THE TEXT

picture intelligence; control could also be effected by making R1 variable, but this arrangement is less satisfactory as the value of R1 must be selected to fulfil another condition, namely, that the flow of anode current increases rapidly after commencement in order that the action of the circuit on the discharge valve is decisive.

THE COMPLETE RECEIVER CIRCUIT

It is now possible to deal with a complete television receiver stage by stage, as circuits which are basically peculiar to television have now been explained although they will be met with again in due sequence and in different forms. Fig. 12 shows the radio-frequency amplifier, frequency changer, intermediate frequency amplifier and vision detector (usually called video detector) of a purely experimental television receiver. The aerial consists of a simple dipole using a twin feeder terminating in an aerial coil which is inductively coupled to the first grid coil, an electrostatic screen being interposed to prevent capacitive coupling; this arrangement is conducive to a favourable signal-to-noise ratio as the grid of the radio-frequency amplifier is operated almost entirely by energy picked up by the dipole itself, which should be as remote as possible from sources of interference, while energy picked up by the down-lead is balanced out, this matter is referred to later under " installation.".

R.F. Stage

In the brief space available little need be said regarding the R.F. stage except to point out that its prime function is to improve signal-to-noise ratio and to assist in preventing re-radiation. High gain cannot be expected owing to the low dynamic resistance obtainable from a coil tuned to such a high

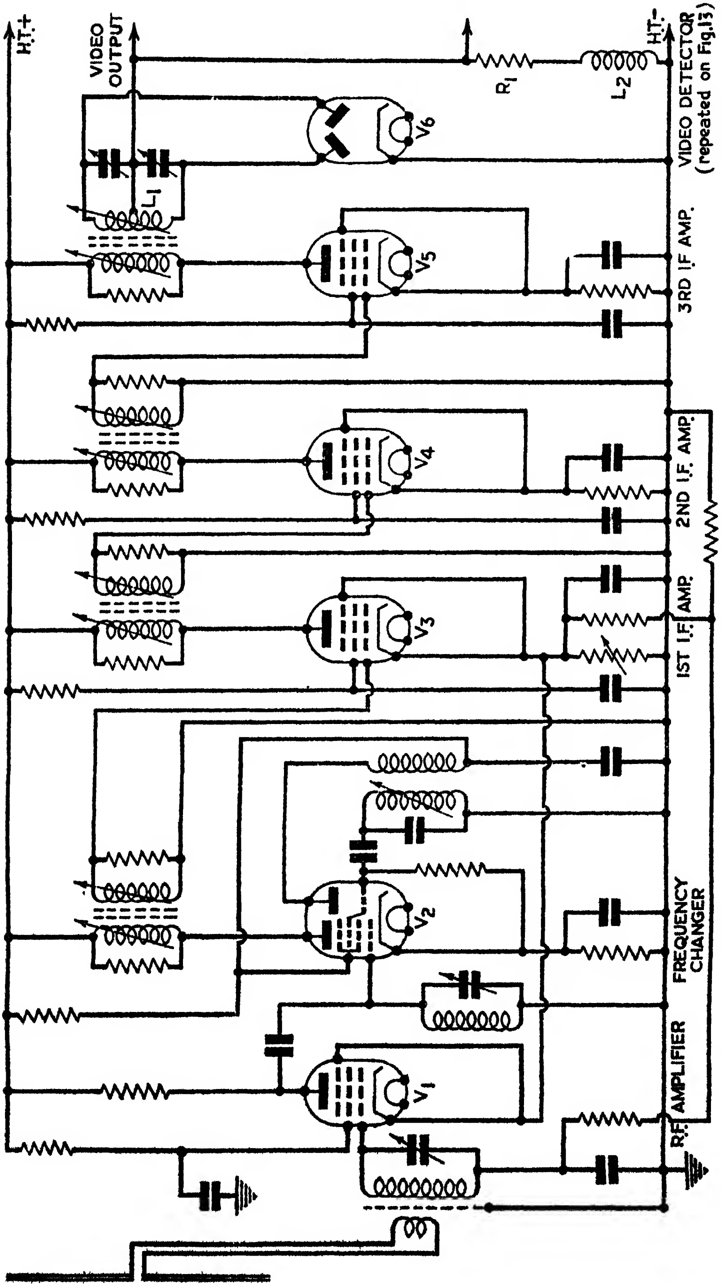


FIG. 12.—THE CIRCUIT DIAGRAM OF A COMPLETE TELEVISION RECEIVER WHICH IS CONTINUED AT FIG. 13.

frequency. It is convenient to take this opportunity of mentioning that automatic volume control is not generally used in television partly because the direct ray is used, television from a reflected signal being impracticable. In addition, the arrangement of A.V.C. would be extraordinarily difficult as no steady carrier exists and the amplitude of modulation may vary widely and such variation may be maintained over fairly long periods.

It cannot be over-emphasized that the service area of television is limited and that although interesting, freak reception over long distances does much to harm the establishment of television as a normal means of entertainment. It is interesting to record, however, that the writer was successful in receiving the Rome television transmitter (before the late war) on three consecutive evenings at a South Coast town for a short period when transmission did not overlap that originating from the B.B.C. transmitter at Alexandra Park. Fading was extremely bad and on the third occasion a form of A.V.C. was tried which appeared to make some small improvement.

Before leaving the R.F. amplifier, it is necessary to introduce two basic variations in design. The vision and sound receivers may be entirely separate except perhaps that they may share a common power pack or a portion of the circuit may be common to both; the R.F. amplifier and frequency changer often perform this dual role, in which case the R.F. amplifier must be designed to cover both the sound and vision frequency.

Frequency Changer

The design of the frequency changer is perfectly orthodox in principle, although two tuned circuits may appear in its anode circuit if it is common to the reception of both sound and vision. Two points must be watched, however, signal-to-noise ratio and frequency stability of the oscillator; commenting on the former it is perhaps unnecessary to draw attention to the fact that signal-to-noise ratio is more important on vision than on sound, as the eye is far more intolerant than the ear. Commenting on frequency stability, it is obvious that this quality is desirable on any receiver, irrespective of whether it is intended for sound or vision, but in the particular case of television an unstable

frequency introduces an additional complication, since it will often produce traces of the sound broadcast on the cathode-ray screen, causing various patterns sometimes reminiscent of watered silk. Various methods are available of improving oscillator stability, but special mention may be made of negative feedback which is becoming increasingly popular for effecting this improvement; some receivers are fitted with automatic frequency control.

When sound and vision receivers are combined, it should be understood that a single oscillator frequency is injected into the mixer valve which produces two intermediate frequencies when combined with the vision and sound frequencies respectively, two intermediate frequency transformers or other forms of tuned circuit being used in series as the anode load; it is interesting to note in this respect that entirely different forms of coupling can be used in series, for example, transformer coupling for the vision intermediate frequency and tuned anode for the sound intermediate frequency. An arrangement which requires that the output of the two tuned circuits are in parallel, although the actual inductances are in series if a common I.F. amplifier is used.

I:F: Stages

Before proceeding to considerations of the intermediate frequency amplifier, attention must be given to the band width which the vision intermediate frequency amplifier must handle without serious attenuation. A normal broadcast transmitter can usually be accommodated without detrimental effect if the receiver is designed to pass a band width of 9 kc/s.; for television sound, however, 15 kc/s. is desirable, as the B.B.C. have taken advantage of the increased "elbow room" to radiate higher quality transmissions. The vision transmission, however, requires very much greater band width, 2 megacycles is often considered satisfactory, although a wider band width is advantageous; on the other hand, 1·5 megacycles may be regarded as the minimum for tolerable reception. Clearly, such a wide band width calls for tuned circuits of special design which unavoidably result in lower gain than that associated with sound transmitters. The wide band width is usually achieved by the use of over-coupled circuits, which are fairly heavily damped;

it will be observed in Fig. 12 that resistors are connected across both primaries and secondaries of the intermediate frequency tuned circuits.

The Detector Stage

Mention has already been made of the necessary wide band width and it is not surprising that this greatly influences the design of the detector circuit, that shown at Fig. 12 is of the double wave type and is sometimes met with in sound receivers; the radical difference lies in the choice of anode load which is very low, this is unavoidable owing to the danger of serious attenuation of the higher video frequencies caused by the shunting effect of parallel capacity made up by the valve and stray capacities. Common values for the anode load lie between 1,500 and 2,000 ohms, and to offset what would otherwise be a serious stage loss in the detector circuit a special type of diode valve is employed having a very low impedance; in the example illustrated, the detector diode load is partly resistive and partly inductive, the intention being to accentuate the higher video frequencies. It is essential that the intermediate frequency be filtered out from picture intelligence and a suitable filter arrangement usually appears in the detector output circuit.

When designing the video detector, the circuit must be so arranged that the cathode-ray tube is driven in the right direction, that is to say, an increase of modulation must drive the grid of the cathode-ray tube in the positive direction. The output of the video detector is normally insufficient to drive a cathode-ray tube of conventional dimensions and an amplifier is usually interposed; this amplifier follows the detector and in this respect resembles the first audio-frequency stage in the sound receiver. As it is amplifying vision frequencies, it is known as the video amplifier, the valve is usually but not necessarily a pentode; it will be observed that a further attempt is made to compensate loss due to attenuation of the higher video frequencies by making the anode load of the video amplifier partly inductive, there is, however, a limit to this type of compensation as over-compensation can produce some very undesirable results, it is in fact often difficult to compensate to an extent which materially exceeds the loss due to parallel capacity in the detector and video amplifier respectively.

The Black Spotter

Before considering Fig. 13, which shows the latter half of the same television receiver, mention may be made of a circuit innovation known as the black spotter; white spots on the picture are irritating enough in themselves, but when the amplitude of the interference materially exceeds the strength of the signal, the nuisance value is greatly increased by the cathode-ray beam being de-focused due to the cathode-ray tube being driven too far in the positive direction which increases the size of the spot. To overcome this difficulty a diode may be interposed which commences to operate when the grid of the cathode-ray tube would otherwise be driven more positive than necessary for the production of maximum white, the output of the diode is then employed in such a manner that the grid of the cathode-ray tube is driven in the negative direction; thus, if the amplitude of interference slightly exceeds maximum white, the tendency to de-focus is checked. If the amplitude of interference reaches an even greater value, the spot—at the instant of interference—is decreased in brightness and, if the interference be great enough, reduced to black. The black spotter is obviously only useful for mitigating the effects of interference which is of short duration and relatively infrequent, into which class may be included interference from motor car ignition systems. This device is sometimes called an interference inverter or sometimes simply an inverter.

Video Circuits

Attention may now be directed to Fig. 13, which shows that portion of the television receiver which includes the video detector, the video amplifier, the line and frame time bases and the cathode-ray tube and comprises that portion which is peculiar to a television as distinct from a sound receiver, for convenience the video detector is repeated from Fig. 12. In order to broaden this brief description of television technique, the circuits shown differ from those which have been used in previous pages and are arranged to meet the requirements of a cathode-ray tube employing magnetic deflection and focus, a type that is now in general use, whereas time bases previously explained have been arranged for use with a cathode-ray tube using electrostatic deflection. This circuit is that of a television receiver built by

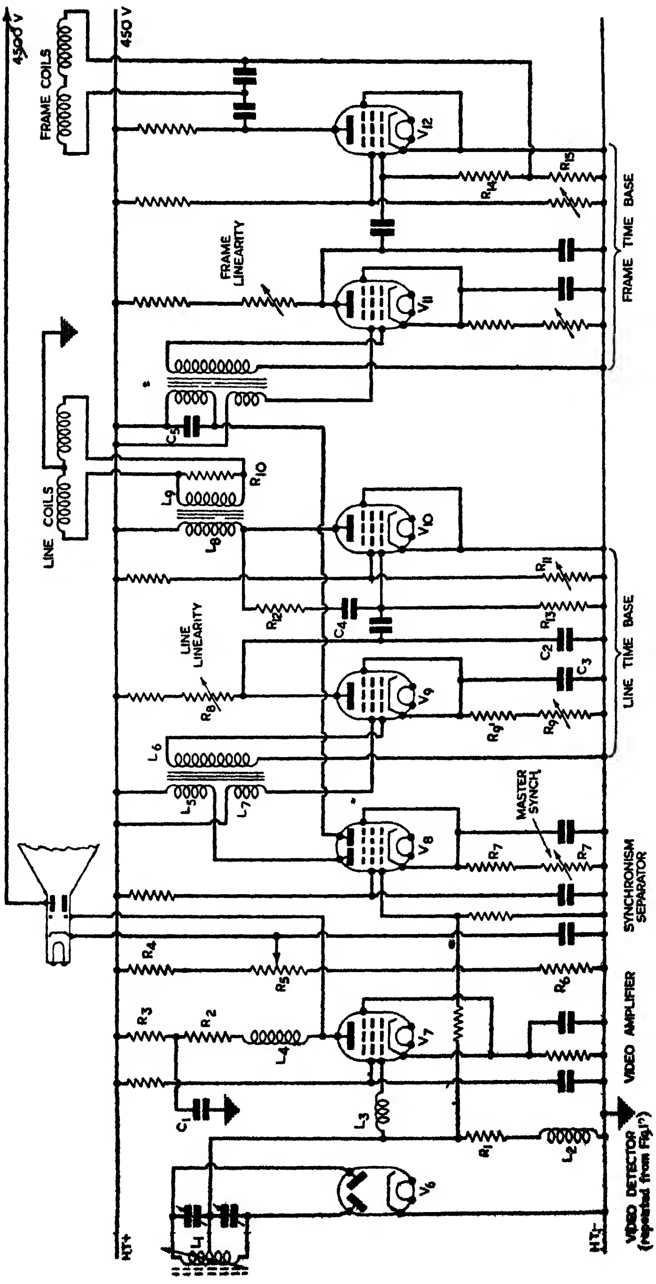


FIG. 13.—THE CIRCUIT DIAGRAM OF A COMPLETE TEVEVISION RECEIVER WHICH IS CONTINUED FROM FIG 12

the author personally, although no novelty whatever is claimed for it, the design being admittedly influenced to some extent by convenience and the availability of components.

Cursory examination of Fig. 13 will show that V6 is the video detector, V7 is the video amplifier, V8 is the synchronism separator, V9 and V10 are the line discharge and amplifier valves respectively, and V11 and V12 are the frame discharge and frame amplifier valves respectively. As already mentioned, the cathode-ray tube is of the magnetically focused and magnetically deflected type, the anode being held at a potential of 4,500 volts which is variable within narrow limits to act as a vernier focusing arrangement; the H.T. positive line of the extra high voltage supply may be earthed in preference to the H.T. negative line. Magnetic focusing is achieved by an energized coil and by varying the current passing through it, focus is roughly adjusted; a vernier adjustment could have been provided in this circuit, but the arrangement adopted was more convenient. Contrast control takes the form of variable bias on the R.F. and first I.F. amplifier (see Fig. 12), the intention being so to adjust this control that the tube is fully modulated when the received signal is 100 per cent. modulated (see Fig. 14), as will be seen later when the adjustment of a television receiver is discussed.

It is now possible to consider Fig. 13, stage by stage, beginning logically with V6 which is the diode detector repeated from Fig. 12; the tuned circuit L1 being the secondary of the last I.F. transformer. As already stated the diode load consists of the resistor R1 and the inductance L2, the latter being included to improve the amplitude of the higher video frequencies. The top end of the diode load is connected to the grid of the video amplifier through a filter consisting of L3 and stray capacities; V7 is biased by a resistor in the cathode circuit in the normal manner and works into a combined resistive and inductive anode load R2, L4, de-coupling being provided by R3, C1. The anode of the video amplifier is directly connected to the grid of the cathode-ray tube which means that the cathode must be connected to a point which will give it a potential equal to the anode potential of V7 plus the bias voltage required by the tube; this positive voltage is provided by the potentiometer network R4, R5, R6, R5 being a potentiometer giving adjustable grid bias to the cathode-ray tube which is in fact brilliance

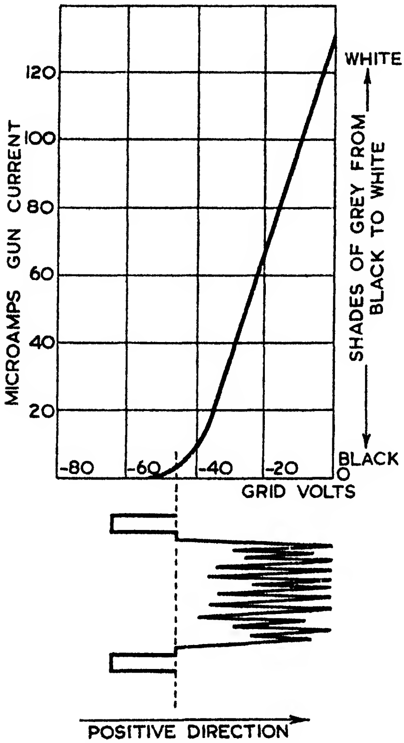


FIG 14.—THE MODULATION OF THE CATHODE-RAY TUBE.

control and is adjusted so that the cathode-ray tube is biased to cut-off.

This arrangement of the D.C. grid and cathode potentials of the cathode-ray tube may seem peculiar until it is remembered that it is immaterial whether the grid is made negative in respect to the cathode or the cathode made positive in respect to the grid, the electron stream being influenced solely by the difference and polarity between grid and cathode. It may also appear strange that a capacitor is not interposed between the anode of V7 and the grid of the cathode-ray tube to overcome the difficulty of the anode voltage of the former appearing on the grid of the latter. The use of a capacitor in this position would unfortunately pass only the video-frequency components of the televized signal and the D.C. component would be lost and would need to be restored by the use of an additional diode or by other convenient means. D.C. restoration is in some ways advantageous; in the circuit under consideration the alternative method of direct connection was adopted.

The top end of the diode load R1, L2 is also connected to the grid of the synchronism separator valve V8, which is of the split anode type referred to previously in this chapter, the diode detector V6 is so arranged that an increase in modulation drives the top end of the diode load in the negative direction; in other words, the received signal is upside down as shown at Fig. 15, this is, of course, reversed by the video amplifier so that the cathode-ray tube is modulated in the right direction. The reverse requirement, however, obtains in the synchronism

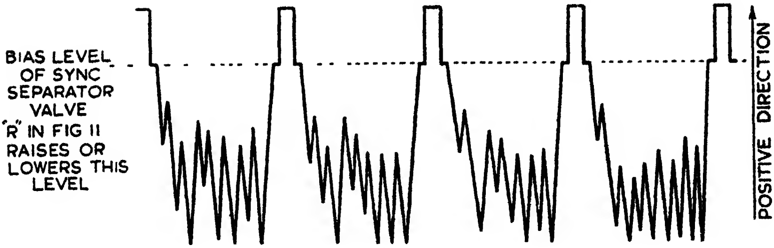


FIG. 15.—THE RECEIVED WAVEFORM IS FED TO THE SYNCHRONISM SEPARATOR SO THAT IT IS INVERTED.

separator valve as it is desired to ignore picture intelligence, consequently the valve is biased so that the grid is negative by a voltage which approximates 70 per cent. of the peak to peak signal voltage developed across the video detector load. Thus 70 per cent. modulation of the incoming signal just cancels out the bias, but a further increase which occurs on the instance of the transmitted synchronism pulses (do not forget that the transmitted wave-form has been turned upside down) will cause anode current to flow, the value of which will rise abruptly if the screen voltage is carefully chosen for V8. As will be seen later, this sharp increase of anode current is used to trigger the line and frame time bases respectively. In passing it may be mentioned that an ordinary single anode pentode could be used, but it would be necessary to make arrangements to prevent interference between the two time bases which are quite independent of each other when using the split anode pentode.

Line Time Bases

A glance at Fig. 13 will show that line and frame time bases are similar in principle but differ in detail. The arrangement used for the discharge valve is interesting, R8, of which a portion is made variable, and C2 are the now familiar charging resistor and capacitor, and R9, of which a portion is made variable, will determine the negative grid bias on the discharge valve V9. The action is as follows ; starting from the instant immediately following discharge, the voltage across C2 will be small and the grid bias will be high. The voltage across C2 is also the anode voltage of V9, therefore, no anode current will pass, but this condition will immediately commence to alter since (i) C2 will

charge up through R8 and the anode voltage of V9 will increase and (ii) coincidentally the grid bias will decrease as C3 discharges through R9.

Presuming that the value of R9 is correctly set, a condition will be reached when anode current is almost, but not quite, ready to commence flowing when the line synchronism pulse is received. This will cause the appropriate anode of V8 to pass current which will flow through L5 which is so wound with respect to L6 that the grid of V9 is driven positive to an extent which causes this valve to pass anode current immediately.

When V9 passes current it will also pass screen current which will flow through L7 which is so wound in respect to L6 that the grid of V9 is driven still further in the positive direction ; this again increases anode current which also increases screen current which by virtue of the coupling between L7 and L6 drives the grid of V9 still more positive, thus producing the desired snowball effect resulting in the rapid discharge of C2. Discharge is completed by the voltage across C2 becoming very low. The heavy anode current through V9 during discharge must flow through R9, thus building up the voltage across C3 and the condition is then similar to that obtaining at the beginning of this explanation. It is apparent that C3 is not merely the by-pass capacitor but a reservoir capacitor which maintains the necessary negative grid potential on V9 while C2 is charging.

It will be observed that the circuit of V9 is not connected to the deflection arrangements of the cathode-ray tube and in this respect differs from time bases described earlier in this chapter, entire control of the cathode-ray tube being performed by the line time base amplifier V10. As C2 charges, the grid of V10 is driven in the positive direction resulting in an increase of anode current which flows through the primary of the output transformer L8, L9, feeding the line deflection coils. Considerable care is necessary in design as an anode potential of the order of 2,000 volts is built up, although the applied H.T. voltage is only 450 volts and the valve selected for V10 must be specially flashed to remove any traces of barium which may be on the internal insulating surfaces of the valve.

The transformer L8, L9 also requires careful design and, as will be seen, a resistor R10 is shunted across the secondary to limit the peak value. With the experience available before the late war such transformers were very difficult to design,

particularly if reasonable considerations of size and economy had to be observed, but greater problems had to be faced in designing somewhat similar transformers to meet demands made by the development of radar. During the war the technique of manufacturing such transformers to withstand far greater strains was satisfactorily mastered, and this experience is available as a significant contribution to post-war television design.

The line charging resistor R8 is partly variable and will determine the voltage difference appearing across C2 at the instant of charge and discharge respectively and will obviously influence the maximum and minimum anode current of V10; this however, can be offset by adjustment of R11 which controls the screen voltage of V10 and, therefore, its amplification. Obviously there are numerous combined settings of R8 and R11 which will give the required deflection of the cathode-ray beam and correspondingly the required line length or picture width, but there is one particular combination which will give the best linearity and since adjustment of R11 has the greater apparent influence on picture width, this control is so designated and R8 is designated line linearity; this method of obtaining acceptable linearity is assisted by negative feed-back to the grid of V10, the extent of which is determined by the relative value of R12, R13, the latter also acting as grid current bias resistor. C4 is interposed between R12 and the grid of V10 merely to isolate the anode voltage.

Frame Time Bases

Attention can now be turned to V11 and V12 which form the frame time base and differ from the line time base in three particulars. (i) A capacitor C5 is connected across that portion of the discharge transformer which is in the anode circuit of the synchronism separator valve V8 to introduce the necessary time constant so that the effect on V11 of the line synchronism pulse is insignificant. (ii) The output arrangements of the frame time base amplifier valve V12 are modified as the deflection in the frame direction is less than in the line direction; (iii) the method of negative feed-back is altered and is achieved by connecting the free end of the frame deflecting coil to a selected point in the grid circuit of V12, the amount of feed-back being determined by the relative values of R14, R15, which together

form the grid current bias resistor to V12. By comparison it can be seen that the same methods are used for the control of synchronism, linearity and picture height in the frame time base as are used to obtain similar control in the line time base.

Before leaving Fig. 13, it is perhaps interesting to record that when the television receiver on which this circuit is based was originally constructed, exactly the same type of time base was used for the line time base as for the frame time base (excepting, of course, that C5 was omitted) and was quite satisfactory for a cathode-ray tube giving a picture about 9 inches wide but when a larger cathode-ray tube was employed, giving a larger picture, it was necessary to modify the line time base to that shown in Fig. 13 to obtain the greater deflection necessary for the wider picture.

The Power Pack

In so far as space permits, all aspects of the actual television receiver design have been touched upon with the exception of the power pack, which is necessarily more elaborate than that associated with a normal broadcast receiver, since two entirely separate high-tension outputs are required; one having a relatively low voltage high current output, say 450 volts, 100 mA, and the other having a very high voltage and very low current output averaging in the neighbourhood of 4,500 volts, 50–300 microamps. While alternative means are within the bounds of feasibility, it is convenient to use two entirely separate mains packs having nothing in common except the on-off switch and possibly a common chassis. For the purposes of this chapter the normal high-tension power pack can be ignored since it is adequately dealt with elsewhere and consideration can be given to the extra high-tension power pack, usually abbreviated as E.H.T., a typical circuit being shown at Fig. 16.

Little need be said about the arrangement for the rectifier valve, but points of interest arise regarding the actual rectifier valve itself and the smoothing circuit. The former must be specially designed for high voltage use and has the anode connection brought out to the top cap as a convenient means of producing the high insulation necessary to withstand the high voltage difference between anode and cathode, which may be as high as 5,000 volts R.M.S., which is 7,000 volts peak. The

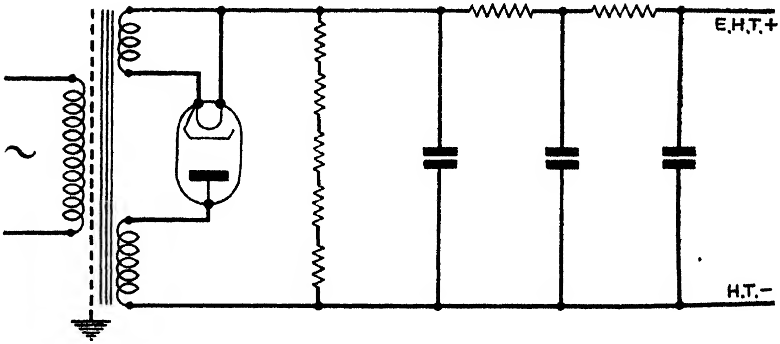


FIG. 16—A TYPICAL E.H.T. POWER PACK.

design of the actual electrode assembly is influenced by the low anode current output which is limited to a few milliamps.; the cathode is usually of the indirectly heated type and often has a deliberately extended heating up period to ensure that the time base valves are functioning before the cathode-ray tube beam current begins to flow in order to prevent the fluorescent screen being burned by a stationary spot.

It will be seen that resistors are used in place of the usual smoothing choke which is both satisfactory and convenient since values as high as 0·25 megohms may be used without excessive voltage drop owing to the very small current flowing which, as already intimated, is usually between 50 and 300 microamps. The smoothing capacitor can be relatively small in view of the high value of the associated resistors, an economy which is very desirable, as capacitors capable of withstanding such high voltage easily become both bulky and costly; the smoothing capacitors are usually shunted on the valve side by a number of resistors in series, making a total of perhaps 25 megohms in order to discharge the capacitors when the receiver is switched off, this shunt resistor is called a bleeder and its provision is greatly appreciated by service engineers who might otherwise receive electric shocks of unpleasant violence if the precaution of discharging the capacitors were overlooked. Electric shocks at the voltage indicated are exceedingly unpleasant but harmless in normal circumstances, as the maximum current is limited by the smoothing resistors to a few milliamps. It may perhaps be explained that the reason for using a number of resistors in

series instead of a single resistor of equivalent value, is to obviate the danger of flash-over which might well occur with a voltage difference of some 4,000–5,000 volts across a single resistor having a length of perhaps 2 inches; for similar reasons the resistors are sometimes unpainted.

Before leaving the subject of the power pack, attention may be drawn to the need for very high insulation between transformer windings which accounts for preference being given to a separate E.H.T. transformer instead of using a common core and primary winding; it may also be usefully noted that some television receivers use the same high–tension power pack to supply the sound receiver as well as the time bases, video amplifier, etc., whereas in others separate power packs are employed to permit the use of a standard broadcast receiver with an additional television frequency band.

INSTALLATION OF THE RECEIVER

The installation of a television receiver is important, if the greatest benefit is to be derived from the entertainment value which this modern service offers. Two major considerations are the placing of the receiver in the room and the aerial system, the former is important anywhere, but the influence of the latter becomes rapidly more important as distance from the transmitter increases. The fact must never be lost sight of that while field strength decreases rapidly with distance, local interference is often unabated and may even be worse at a point remote from the transmitter, say when the aerial is close to an arterial road carrying a large volume of motor traffic which regrettably will include a large number of vehicles which are not fitted with suppressors in their ignition systems.

Motor ignition interference is invariably quoted, owing to its widespread prevalence, but more vicious forms of interference exist, although, fortunately, they are less frequently met with, a peculiarly devastating form of interference is that arising from medical diathermy apparatus if it happens to use a frequency close to that employed for television; fortunately, such equipment is in the hands of responsible people who, if the writer's experience may be regarded as typical, are very willing to shift the frequency if approached in the proper manner.

The Aerial

The general form of the television aerial is well known and usually has the appearance of either a single rod or two rods suitably spaced in the form of the letter H, these aerials are known as dipoles and reflector dipoles respectively, and the aerial dipole as distinct from the reflector may be split in the centre for the purpose of making connection to the receiver or may take the form of a single rod, connection being made from the lower extremity. In the former case, connection is made directly by a double conductor which is known as a feeder. When connection is made at the end of the dipole, some matching device must be incorporated which performs the function of a transformer, although singularly different in appearance.

Whatever type of aerial is used, height is the all important factor, since an increase of this quality will make greater signal strength available and tend towards a decrease of local interference, particularly when the source is immediately below the aerial. Theoretically, the feeder should leave a centre fed dipole at right angles for a distance of not less than one quarter of a wavelength, but such an arrangement presents such a grotesque appearance when the aerial is mounted on a mast, that most people will ignore this requirement unless the aerial is out of sight. The length of a dipole is fairly critical, but aerials supplied by different manufacturers vary considerably in length; this apparent paradox is due to the fact that the critical value is the natural wavelength of the aerial and since length roughly determines inductance and diameter capacity, it follows that one dimension is influenced by the other. Since a single aerial is used for both sound and vision reception, some dipoles are designed so that they are tuned to vision frequency while others make some concession in the direction of the sound frequency.

Aerial Feeders

Two types of feeder are in common use, the twin feeder which consists of two metallic conductors of pre-determined gauge, accurately spaced and embedded in pliable insulating material, having low electrical loss and high mechanical durability. The alternative type of feeder consists of a single wire running down the centre of woven metal tubing from which it is spaced by low loss insulating material, which often takes the form

of circular insulators at regular intervals; this form of conductor is known as concentric feeder. Whichever form of feeder is used, it must have the correct characteristic impedance which means that a correct relationship must exist between the two conductors; feeders of both types especially intended for television use may be obtained through normal retail channels.

Generally speaking a television receiver, designed for use on twin feeder, should not be used with concentric feeder and *vice versa*; a receiver intended to be used with a twin feeder has an aerial coil with a centre-tapped earth or no earth connection and works on the principle that energy picked up by the feeder (which often passes through a high interference zone) appears at the ends of the coil at equal amplitude but opposite phase which does not permit of such energy moving through the coil, whereas energy picked up by the two arms of the dipole are in opposite phase; this results in a movement of current through the aerial coil and transference of energy to the grid coil, the voltage developed across which operates the first valve. The concentric feeder requires that its outer conductor is earthed and consequently the aerial coil is earthed at one end. Before the war much controversy existed regarding the relative merits of these basically different feeders, the argument in favour of the concentric feeder being lower loss and the argument against it being that the effectiveness of the outer conductor as a shield decreased progressively from the point where it was earthed.

During the war considerable development took place in the manufacture of low loss insulating material, consequently the case against the twin feeder is thereby weakened. It is impossible, however, to do justice to this argument in the space available, unfortunately mismatching between feeder and receiver is all too common.

Receiver Location

Advice on the position in which a television receiver should be placed in the viewer's home may seem a matter to be decided by the viewer's convenience or fancy, but there are one or two points which should be borne in mind. Other things being equal, the receiver should be placed as near to the point where the feeder enters the room as possible, but the paramount consideration is usually lighting; a position must be found where any

source of light which it is desired to keep on while viewing (and this includes the fire), must not shine on the face of the tube, neither should the viewers look past the receiver at a source of light or any object which will reflect it. Another point of convenience that should be borne in mind is the desirability of reducing to a minimum the moving of furniture from its normal position to that which is convenient for viewing.

Optimum Viewing Distance

The actual optimum viewing distance must on occasion be controlled by the number of people who wish to view but generally speaking, the ideal position is at that distance where four fingers extended at arms length will just cover the screen. If the television receiver is of the type requiring the use of a normal broadcast receiver to provide the sound, it is essential in the interests of realism that the loudspeaker be placed as near to the screen as possible, or even behind the television receiver. If the direction of sound differs greatly from the direction of the picture, the illusion is completely lost and it becomes evident that the voice is not emanating from the performer.

Adjusting the Receiver

The adjustment of a television receiver is extremely simple and comes with familiarity and, furthermore, sharp differences occur between receivers regarding the number of controls placed for operation by the viewer; some receivers have the essential controls on the front and what might be termed the pre-set controls placed, say, on the back. Other receivers make a further sub-division and provide those back controls with knobs which they consider the viewer capable of adjusting, the remainder having a slotted head and requiring a screw driver or coin to turn them. Dealing first with the controls placed for day to day use, these will probably include some or all of the following. Focus, contrast, brightness, tuning and possibly picture hold which is a colloquialism for synchronism; it will be convenient to deal with these in the order given.

Focus should be adjusted until the white lines are as narrow as possible or conversely, that the black spaces between them are

as wide as possible; this may appear unpleasant when viewed a foot or so from the screen but the black lines will disappear at the correct viewing distance. If it is not possible to focus through the optimum point and beyond, it usually means that a vernier is being manipulated and some adjustment is necessary to the main focus control situated elsewhere.

Contrast control may or may not be intended for day to day use, but if it is so positioned, its action may be confused with that of the brightness control, various combinations will produce effects varying from " soot and whitewash " to a general flatness; until the knack of adjustment has been acquired, the following procedure may be found useful. Withdraw the aerial so that no signal is obtained and darken the room to the customary extent for viewing, next increase brightness until the raster can just be seen and then gently decrease until the raster is *just* lost. Care is necessary as the brightness control on some receivers has a slight time delay. Next connect the aerial and adjust contrast until a good picture is obtained; remember that the brightness control should bias the tube to the threshold of " action " and the contrast control (which is simply intermediate frequency gain) should be adjusted so that 100 per cent. modulation drives the spot to dead white but not beyond.

Tuning is simple when a single control is used for vision and sound; it should be adjusted for maximum sound quality and if all is well, maximum picture quality will be obtained automatically. If tuning is for vision only, care is necessary, if the the receiver is designed to use both sidebands of the transmission, tuning is optimum when the picture is brightest, but if only one sideband is used, tuning should be adjusted for maximum picture detail which will not coincide with maximum brightness. If adjustment of tuning produces the impression of watered silk on the tube, it is probable that adjustment is incorrect, resulting in sound entering the vision receiver.

Picture hold if fitted, is usually a means of adjusting the synchronism separator to deliver synchronism pulses of optimum amplitude to the line and frame time bases. It should be swung so that the middle point is found of that portion in which a steady picture is obtained, the picture should then be critically examined to see whether it is interlacing properly; if not, correction should be attempted by a slight movement of this control.

A wide variety of controls may appear at the back of the receiver and to those who have read this chapter with attention the meaning of line hold (also known as line synchronism), frame hold (frame synchronism), picture height (frame amplitude), and picture width (line amplitude) will be apparent. The synchronism separator control has already been described under the nomenclature accorded to it when it is placed on the front of the receiver, i.e., picture hold. A word or two may not be out of place regarding linearity control, obviously this must be so adjusted that an object does not vary in its proportions when it moves from side to side or up and down the screen; it will usually be found that adjustment of this control plays havoc with picture height or width as appropriate. Linearity should, however, be correctly adjusted and the size of the picture corrected by the appropriate control, after which linearity should again be checked, since these controls are seldom independent of each other.

Inverter control (black spotter) should be turned so that the device is completely non-operative when interference is not experienced. In situations where interference is present of a type that can be mitigated by the device, e.g. motor car interference, proceed as follows. Adjust brilliance and contrast with *unusual care* and then turn the inverter control very slowly until a point is reached where white portions of the picture just commence to be impaired, next turn the control in the opposite direction so that the white portions of the picture just, but only just, return to normal. As intimated earlier in the chapter, the advantage of this device is most marked when the amplitude of interference appreciably exceeds that of the television signal.

Astigmatism control is fitted to a certain number of receivers in use to-day and is intended to prevent deformation of the spot as it travels along the width of the picture, which has the effect of giving a jagged appearance to vertical lines which are intended to be clean. The method of adjustment differs widely and the manufacturers' instructions should be rigidly adhered to; as these sometimes require the time bases to be put out of action this adjustment is best left to an experienced engineer, as unfamiliarity may well result in burning the fluorescent screen. This is perhaps the most costly error that can be made with a television receiver.

MAINTENANCE

Fault finding in a television receiver can be treated at very great length and if this entire volume were devoted to this subject, it is doubtful whether every aspect could be covered; furthermore, certain adjustments need equipment which is seldom possessed by the amateur. In the interests of completeness and because of its intrinsic interest, a few notes are appended on the more obvious faults. While the writer has no desire to be an alarmist, it is desirable to state quite bluntly that those who are unaccustomed to handling high voltage equipment will be well advised to leave the back of their receiver firmly in place and leave the question of maintenance to those who possess the necessary experience. It is, however, helpful when summoning the assistance of a service engineer to indicate the nature of the trouble so that an intelligent selection of spare parts can be made available.

Illumination Absent.—When no signs of illumination can be seen, even when brilliance is turned to maximum, the three most obvious causes are no E.H.T. supply, a broken cathode ray tube heater or excessive negative bias on the cathode ray tube modulating grid.

Raster Normal but no Picture.—This condition is due to the absence of a signal on the cathode-ray tube modulating grid and may be due to failure in any stage from aerial to video amplifier.

Line and Frame Scan not Operative.—In other words, the raster is absent but a stationary spot appears in the middle of the tube. Switch off *immediately* although it may be too late to save the tube from burning, most obvious cause is the failure of H.T. supply to both time bases or a coincidence resulting in the simultaneous failure of both time base discharge valves.

Picture Height Absent.—In other words only a single line appears horizontally on the screen with the entire picture modulation piled upon it. Obviously the frame time base has ceased to function, one of the most likely causes being failure of the frame time base discharge valve or amplifier.

Picture Width Absent.—See picture height absent. For "horizontally" read "vertically" and "frame" read "line."

Picture Diminished.—Probable cause, abnormal high-tension supply to time bases or rise in E.H.T. voltage due to a breakdown in the bleeder resistor.

Picture too Narrow.—Probably due to lost emission of the line time base amplifier or breakdown of the line output transformer if used.

Picture too Squat.—See picture too narrow. For " line " read " frame."

Frame or Line Time Base Unstable.—If this cannot be cured by re-setting the appropriate controls the trouble may be due to a soft discharge valve, but more probably to a bad connection anywhere in the appropriate time base.

Frame and Line Time Base Unstable.—Faulty synchronism separator valve, a loose connection in associated circuit, or a broken aerial feeder.

Cathode-ray Tube will not Focus.—Usual cause low E.H.T. voltage or softening of the cathode-ray tube, the former will also exhibit lack of brilliance at the normal brightness control setting, the latter cause will be almost invariably accompanied by an enlarged spot or halo.

Excessive Motor Car Interference.—If a sudden increase has been experienced, suspect a break in the feeder if of the twin type, or disconnection from earth of the outer conductor if of the concentric type.

Patterns on the Screen.—If suggestive of watered silk, or Scotch plaid, an unwanted frequency is present in the vision receiver. This may be the presence of the vision sound transmission, due possibly to mistuning of the vision receiver, alternatively it may be due to external interference possibly in the form of re-radiation from a neighbouring receiver (not necessarily a television receiver).

Interference is sometimes experienced in the form of horizontal bars, which may be straight or zig-zag and may be of infinitely complicated design. Suspect interference from diathermy or similar equipment.

Double Images.—Two or any number of images may appear on the screen, the unwanted ones being to the right hand of the original image. This phenomenon is due to the reception of signals from two or more sources, the unwanted ones being reflections from large objects such as gas holders, the trouble can be cured or mitigated by the use of a double reflector type aerial rotated until the optimum direction is found. Double

image should not be confused with a type of white fringe on a sharply defined dark object which is due to over correction or an improperly adjusted intermediate frequency amplifier.

Halo.—An area of very faint light more or less circular in shape superimposed on the picture. This is often the first sign that a cathode-ray tube is going soft and replacement is the only cure.

Scanning Lines Unusually Noticeable.—This effect is caused by failure of the time bases to interlace resulting in only half the number of lines being apparent. Try adjusting the frame, time base very carefully, if interlacing is not then achieved increase contrast a little and try again; some receivers are prone to this trouble if the feeder is left lying in coils or bent back sharply on itself. A feeder should never be longer than is necessary to reach the receiver.

CHAPTER XXV

RADIO DIRECTION-FINDING

DIRECTION finding is, of course, distinct from radiolocation, although it is closely allied to this subject.

Radiolocation is a navigational aid of considerable value for shipping in the vicinity of coastlines and to provide warning of the proximity of other surface craft or obstructions to avert collision. Both the direction and range of the object which is being radiolocated are determined with this system, whereas with normal direction-finding equipment the chief applications are :

(*a*) for fixing the bearings of a ship or aircraft, and

(*b*) for " homing " under conditions of poor visibility, e.g. in fog or at night time.

The subject of approach and blind landing systems for aircraft is not referred to in this chapter, as they hardly come within the scope of general radio direction-finding equipment and their application is limited to machines fitted with special equipment.

Radiation

Associated with every inductance through which a current passes is a magnetic field. Likewise an electrostatic field exists between the electrodes of a condenser. Long before radio communication became a commercial undertaking it had been deduced mathematically that the acceleration of an electric charge will produce an electromagnetic wave in space. This wave comprises an electric field at right angles to a magnetic field. An oscillatory circuit which is capable of radiating energy in this way is known as an open or radiating circuit.

Electromagnetic waves convey energy from the source, either in all directions or confined to certain specified directions according to the design of the radiating system and other factors. The radiation from a vertical wire or loop produces a magnetic field horizontally and at right-angles to the direction of the transmitting

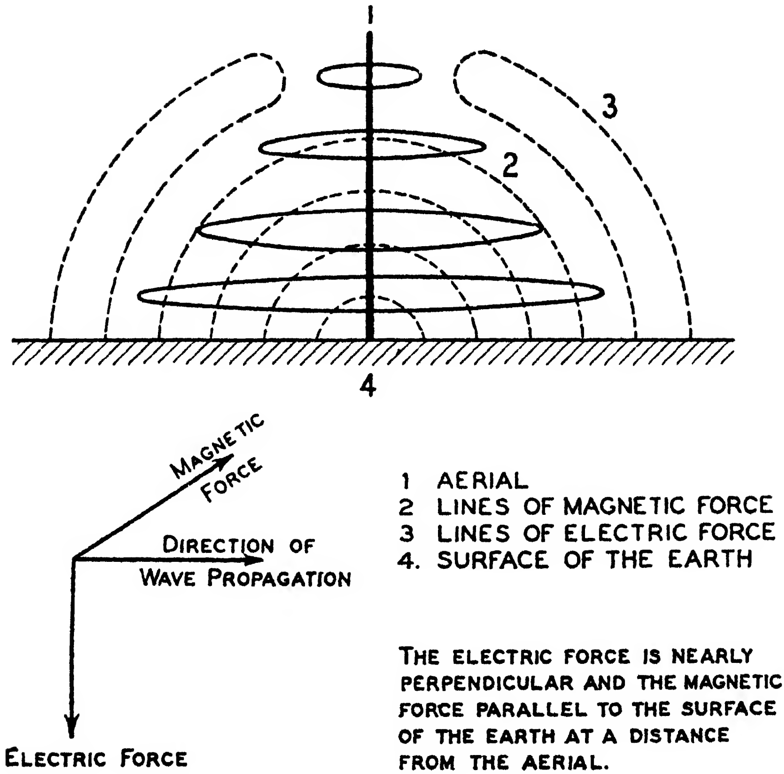


FIG 1—RADIATION OF ELECTROMAGNETIC WAVES

station and an electrostatic field perpendicular to the surface of the earth, as shown in Fig. 1.

Loop Aerials

It will be seen, therefore, that high-frequency radiation at the receiving station can be detected through either the electrostatic or electromagnetic component. In Fig. 2, the arrow indicates the direction of the transmitter from the receiver and the rectangular coil of wire represents a closed loop forming, with the condenser, a circuit tuned to the transmitter frequency. In Fig. 2 (*a*), the plane of the loop is perpendicular to the direction of signal transmission and parallel to the wave front so that the magnetic component induces no current in the loop. The electrostatic component in the ideal case induces equal E.M.F.s in

the vertical limbs, and these in one side oppose those on the opposite side, so that the resultant current is zero. In Fig. 2 (*b*), the linkage of the magnetic component of the field with the loop is a maximum, and maximum oscillatory currents are induced in the tuned circuit.

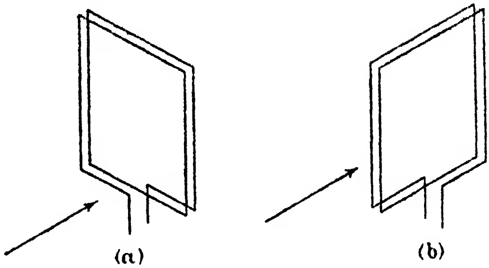


FIG. 2—LOOP AERIALS

Arrow indicates direction of approach of signals from transmitter.

(*a*) Plane of loop parallel to wave front and perpendicular to direction of transmitter. Minimum current induced in loop.

(*b*) Plane of loop perpendicular to wave front and parallel to the line of signal approach Maximum current induced in loop

The signal strength in a receiver with a frame aerial, assuming there are no disturbing influences, depends on the orientation of the plane of the loop and is greatest when this plane coincides with the direction of the transmitting station, decreasing to a minimum and theoretically zero as the loop is rotated through 90 degrees. The direction of the signal approach can, therefore, be determined by finding the position of the loop in which signals are either a maximum or a minimum. All direction-finding equipment utilises this basic principle, though variations arise according to whether the ship, aircraft or the transmitting station has such equipment at its disposal.

Swing Bearings

In practice, the point of minimum signal strength is used for determining signal direction. When signals are weak, it may be possible to turn the frame through an appreciable angle about the minimum point without any signals being heard at all. To assist in deciding where true zero is, it is usual to take what are called swing bearings, i.e., matching the intensity on either side of the indefinite minimum, the midway position between the equal readings being the true zero.

Bearings

Theoretically, the relation between signal strength and frame orientation can be depicted by a figure 8 polar diagram (Fig. 3.), in which the double chord drawn through the common tangent

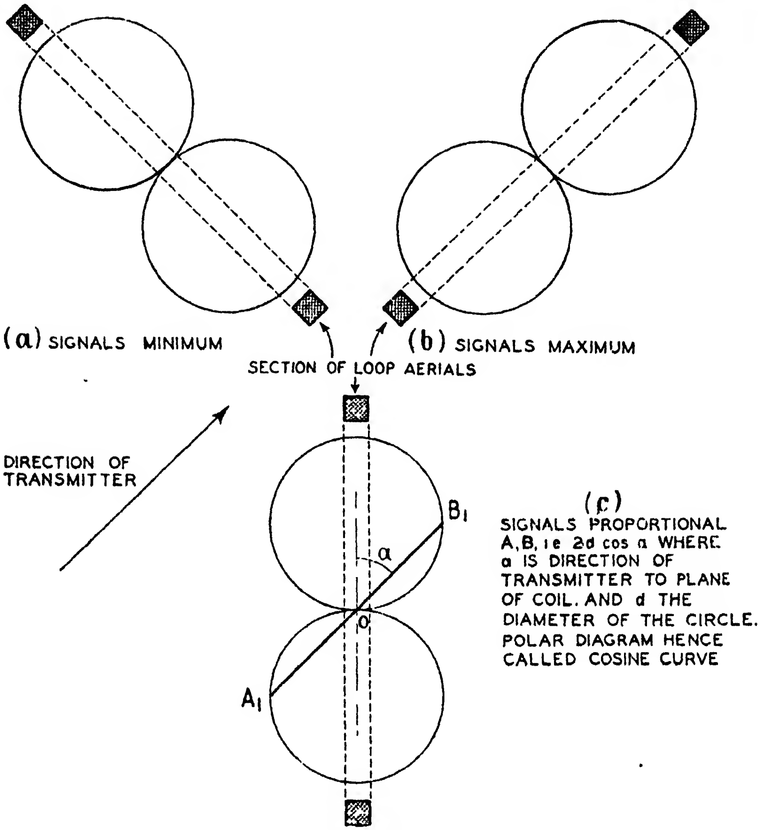


FIG. 3.—FIGURE 8 POLAR DIAGRAM OF LOOP AERIAL.

point is proportional to the signal intensity when the plane of the frame makes an angle, say X, to the direction of signal approach.

If we imagine the line of centres of the polar diagram to coincide with the plane of the frame aerial and to rotate with it about the point O, the signal strength will be proportional to $A_1 B_1$. Thus, if the frame is turned till the signals are at maximum, say X_1 (Fig. 3 (*a*)), and then set so that the plane of the coil is in the line of flight, in which position the signal strength is X_2, then $X_2/X_1 = \cos a$, where a is the bearing of the transmitter station from the line of flight. More simply this information can be obtained by attaching a pointer to the frame, so that it moves over a fixed circular scale graduated in degrees. It is

then only necessary to fix the scale, so that the 0—180 degrees line is due north and south, and with the pointer attached to the frame perpendicular to its plane, to turn the frame until signals are a minimum, when the bearing of the transmitter station from north can be directly read. Alternatively, the pointer can be fixed and the scale rotated with the frame.

Such observations with a frame aerial, assuming the absence of other errors, will determine only the direction of the transmitter, but will give no indication as to whether it is in front of or behind the receiver.

The figure 8 diagram is symmetrical so that the frame can be turned through 180 degrees, and the same indication will be given (See Fig. 5).

Sense Determination

The ambiguity which is thus possible is overcome by the use of an open or non-directional aerial in conjunction with the frame aerial and feeding into the same receiver. The principle of this combination is shown in Fig. 4. An open aerial, being non-directional, produces a circular polar curve and can be made to circumscribe the figure 8 by adjusting the signal strength relative to that received from the frame aerial. If, now, the signals due to the open aerial are exactly in phase with those due to one limb of the figure 8, those in the opposite limb will be in anti-phase. The two curves can thus be combined vectorially, resulting in a cardioid or heart-shaped curve (Fig. 5).

In principle, therefore, a complete observation consists in determining first the bearing of the transmitter station by means of the frame

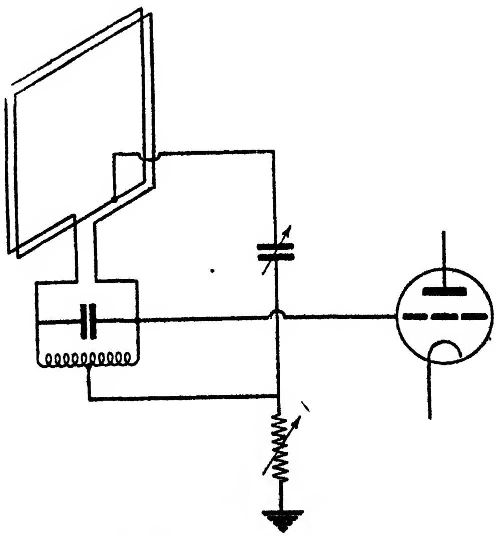


Fig. 4.—Schematic Arrangement of Circuit showing Principle of Sense Determination with Open and Loop Aerials.

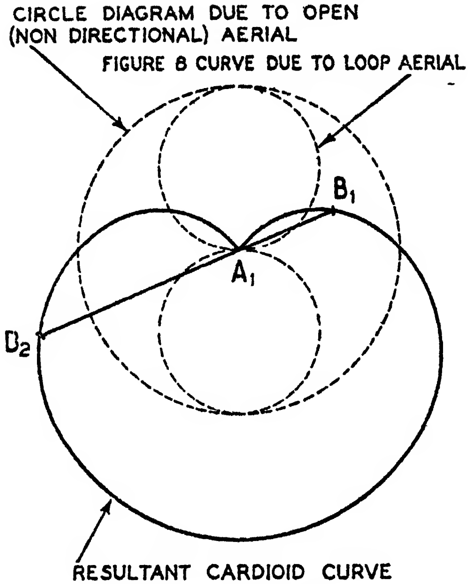


FIG. 5.—CARDIOID DIAGRAM.

aerial alone, as previously outlined. This fixes the AB direction. The open aerial is then brought into circuit and signal strength observed first with the frame in one position and then with the frame reversed, either turned through 180 degrees or reversed in connection by means of a change-over switch. These readings will correspond respectively with A_1B_1 and A_1B_2, which can be distinguished in direction by their relative magnitude (Fig. 5).

The basic principles of the circuit are shown in Fig. 4 of which many modifications are in use. It will be clear that this principle, though simple, depends in practice for its success on the absence of disturbances which falsify the readings. Practical apparatus for direction finding is often elaborate because it must include accessories for secu. the three essentials which the application of these principles demand, viz. (1) elimination of reception errors, (2) correct phasing of frame and open aerial signals, (3) correct relative signal intensity in the two cases.

Errors

Though simple in theory, the use of the frame aerial for direction finding is liable to disturbances from several sources and correction of possible errors is essential before reliability can be secured. The complete discussion of errors is too involved to be treated here, and the chief points only will be mentioned. The principle causes of inaccuracy are :

(1) Antenna, or out of phase, vertical effect. This arises from unequal E.M.Fs. being induced in the two vertical limits of the frame owing to slight differences in their respective capacities to earth, producing a distortion of the polar diagram.

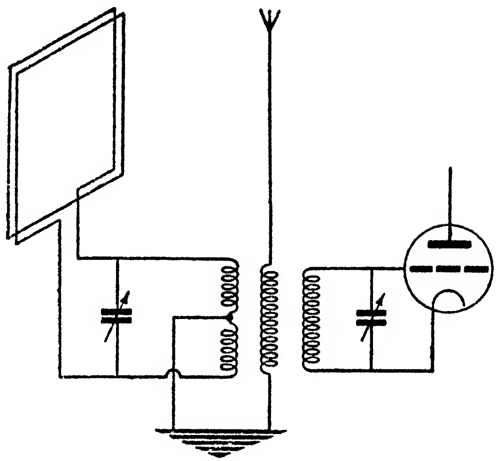


FIG. 6.—PRINCIPLE OF COMBINED OPEN AND LOOP AERIAL.

Vertical error is proportional to the linear dimensions of the frame, while signal strength is proportional to the square of these dimensions, so that its effect is less the larger the frame. The error is independent of the orientation of the frame. Correction of antenna effect can be secured by the use of a symmetrical design of frame with an earthed electrical centre and by suitable earthed shielding to eliminate electrostatic coupling between aerial and tuned grid circuits.

(2) Direct pick-up. This cause of trouble is avoided by the use of suitably disposed earthed shields.

(3) Quadrature, or random phased re-radiation from nearby conductors. If large enough, it may so distort the polar diagram as to make it approach a circle and give uncertain readings in any direction. To a lesser degree, it results in an indefinite zero in the polar diagram.

(4) Displacement currents, if the turns of the frame are not all coplanar. The frame is then equivalent to a tall thin coil when viewed edgewise and this results in a smaller figure 8 diagram at right-angles to the main one. The net result is again to flatten the zero. The obvious method of correcting this error by using pancake coils results in an increase in out of phase vertical effect.

Open Aerial

The open aerial employed to secure a cardioid diagram is not, as shown in Fig. 4, essentially a separate conductor. The electrical centre of the coil, which does not necessarily coincide with the geometrical centre owing to differences in capacitance of the two sections, can be used for this purpose and an adjustable resistance for securing correct relative signal intensity. This arrangement is shown diagrammatically in Fig. 6.

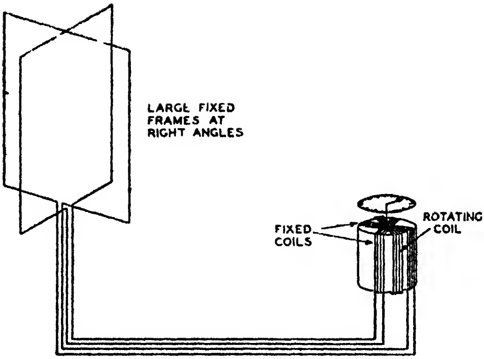


FIG 7—PRINCIPLE OF BELLINI-TOSI SYSTEM OF FIXED FRAME AERIALS WITH RADIO-GONIOMETER FOR GROUND STATION DIRECTION FINDING.

Bellini-Tosi Aerials

To utilize the advantages of a large frame without the inconvenience of a heavy rotating mass, ground stations usually employ one of the modifications of the B/T system (Fig. 7). There is no fundamental difference in this arrangement from that already mentioned. There are two large fixed frame aerials at right angles to one another and these are connected respectively to two small coils, also fixed at right angles. A third, or search coil, is mounted axially with this latter pair and is free to rotate around them. It is closely coupled to the small fixed coils and is connected to a suitable tuned circuit and amplifier. The search coil serves to determine the direction of the resultant flux through the two small fixed coils and with them constitutes what is known as a radio-goniometer.

Several conditions must be fulfilled to secure accurate indications with equipment of this type. The aerials must be identical in size and of the same high-frequency resistance, otherwise indications will not be proportional to the signal strength in the two cases. There must be no magnetic, electrostatic or conductive coupling between the loops. Similarly, the coils of the goniometer field must be identical and accurately at right-angles.

This system can be operated with tuned aerials, simple aperiodic aerials or combinations of frame and open aerial for sense determination, but owing to the critical tuning of the aerial coils with currents in phase which the tuned circuit entails, an aperiodic aerial system is practically always employed. With this system the response to a wide range of frequencies is approximately constant and there is far less mutual coupling, though the decrease in signal strength which results necessitates higher amplification and consequently greater tendency to pick up, so that improved screening is also required.

In the stand-by position, signals are received on an open aerial,

so that some indication is received irrespective of direction. By switching over to D/F, the bearing is obtained when signals are received. Again switching the open aerial in simultaneously and reversing, the sense is determined by the principles previously outlined.

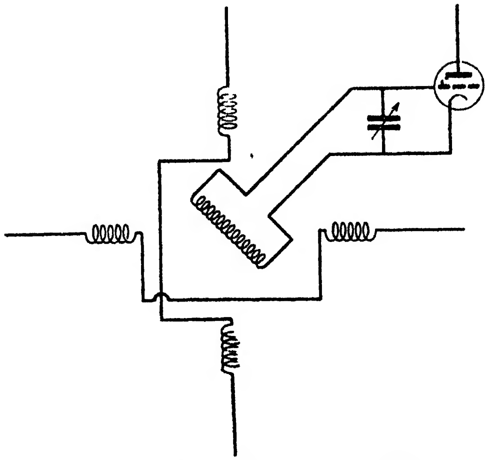


FIG. 8.—SCHEMATIC ARRANGEMENT RADIO-GONIOMETER IN B/T SYSTEM.

The radio-goniometer which is common to all B/T systems varies in design according as the aerials are tuned, aperiodic or combined frame and open aerial for sense determination; the search coil being more closely coupled in the case of periodic aerials.

Directional receiving stations using the B/T system can be designed to employ more than one radio-goniometer in the aerial system, and several traffic services can be dealt with without duplicating the aerial system. Two direction finders can work simultaneously at a central station or two directional receivers can take signals from, or bearings of, two transmitters simultaneously. Multichannel working of this kind is possible by elaboration of the simple fundamental principles outlined.

When a separate heterodyne is employed for the reception of CW. it is necessary to ensure that no coupling exists between this and the radio-goniometer, otherwise the directional properties of these signals will produce a separate pair of superposed minima on the polar diagram.

Several factors have been ignored in describing these fundamentals, particularly errors which occur over long distances due to changes in polarisation and phase angle between direct and reflected waves, the details of which are very complicated and give rise to displaced or indefinite minima.

Adcock Aerials

So far it has been assumed that no voltages are induced in the horizontal limbs of the frame. This is only true if the

waves are travelling horizontally and the wave front is perpendicular to the earth surface. With oblique transmission, as for instance from a plane in flight to a ground station, errors in reading would be produced by the voltages induced in the horizontal limb of the frame so that the frame zero would not coincide with the position when its plane is at right-angles to the line of signal approach.

The chief disadvantage of the Bellini-Tosi system is that it is subject to this type of error and is, therefore, unreliable at night. This is due to horizontally polarised waves being reflected from the Heaviside layer and picked up on the horizontal portions of the loop. From dusk to dawn the reflected wave forms a large proportion of the total signal strength and thus affects seriously the accuracy of the readings. This failing applies to any receiver using a loop, though manufacturers claim to have almost overcome it in some recent sets. The Adcock aerial system is designed to eliminate the effect of pick-up on the horizontal limbs of the frame. In principle it consists of two pairs of open spaced aerials with screened horizontal connections so that reception is confined to the vertical aerials. For short waves, the aerial spacing will be about 20-ft., so that the system is applicable only to fixed ground stations. In application, the principle of the Adcock aerial necessitates many precautions by suitable disposition of the aerial system or otherwise, to ensure that horizontal limb pick-up is zero, or is balanced out. In some cases, the horizontal limbs may be buried and auxiliary circuits employed to remove residual errors.

Since both high and low-frequency stages are usually employed in the receiver unit, disturbances will be sufficiently amplified to give trouble. Cases of considerable difficulty are those where the same site is used as a transmitter and receiver station, though much can be done in the way of eliminating disturbances by the choice of a suitable site for the ground station in respect of power mains, natural objects and other transmitter stations.

AIRCRAFT DIRECTION-FINDING.

Direction-finding equipment for navigating aircraft between airports as distinct from landing or approach systems involves the same basic principles as those previously outlined. They are, in general, similar except in detail to marine D/F apparatus. There is one application known as the homing system which is

peculiar to aircraft and enables the pilot to set his course towards a known transmitter, the nose of the machine being kept heading towards the ground station in question.

The Homing System

In its simplest form, the homing principle involves a loop aerial fixed with its plane at right-angles to the centre line of the machine. In practice, there is also an open or non-directional aerial which can be brought into circuit with the frame by means of a three-position switch. In position (1) the loop alone is connected to the receiver. In position (2) both loop and open aerial are in circuit. Position (3) is the same as (2) but with the loop aerial connections reversed.

If the plane is heading in the line of signal approach or head on towards the transmitter, no signals will be received in the loop aerial and no change in signal strength will be detected when the aerial system is switched from position (2) to position (3) or *vice versa*. On the other hand, if the switching operation produces a difference in signal strength, the true course is to port or starboard of the machine. This system is useful when no D/F ground stations lie on or near the route over which the machine has to fly.

Since the machine is on course when signals are zero without the open aerial, there is the obvious disadvantage of the fixed-coil homing system that the machine must be swung off its course to ensure that signals are still there. Among the devices designed to overcome this is an arrangement in which two identical coils are fixed at an angle to one another with the line of the machine bisecting this angle. On course indication is then shown by no change in signal strength when the coils are switched in and out in turn, an operation which may be carried out by a motor-driven switching device.

Small diameter loops, encased in stream-lined fittings, externally mounted have displaced both the earlier forms of wing coil which often spanned the entire width of the wing and had a superficial area of perhaps 100 sq. ft. and the fixed fuselage coil wound on spacing blocks round the nose of the machine.

Limiting Factors

Two effects which limit the scope of the fixed-coil homing system are: (1) Drift due to wind. (2) Indications from off-course transmitters. Wind drift varies from zero in the direction

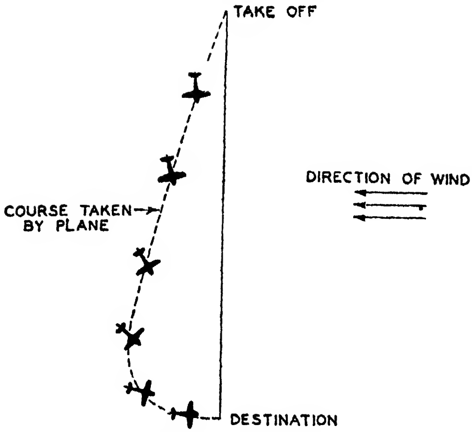


FIG 9—EXAGGERATED REPRESENTATION OF EFFECT OF WIND DRIFT ON MACHINE WITH FIXED COIL HOMING DEVICE

of the line of flight to a maximum in a direction at right-angles to it. The loss in time due to drift becomes less the greater the ratio of machine speed to wind velocity, so that it is relatively less serious for high-speed machines. The effect in causing deviation from the true course is shown exaggerated in Fig. 9. In many cases, the homing transmitter will not be in line with or at the point to which the machine is flying, and the effect of drift will then be greater.

Rotatable Loop System

Correction for this becomes possible by the use of a rotatable loop, which retains the essential feature of the homing system and at the same time provides the operator with D/F equipment for use where there are no D/F ground stations on the route. It also enables some correction to be applied for drift and for the position of off-course transmitters.

For instance, in Fig. 10, OA represents the centre line of the machine and also the direction of its destination. If the homing coil is offset angularly so that it is perpendicular to OB, the direction of the transmitter, minimum signals will be received when the machine is heading along OA. A further offset is made to correct drift. Since wind velocity and direction will vary, the correction must be checked periodically and continually adjusted during the time of flight. A more correct course is thus possible than with the fixed homing coil.

Rotatable Direction-Finding Aerials

Small outboard loops consisting of a number of turns of wire enclosed in a circular metal pipe split at some point of its circumference to avoid a short-circuiting effect on the inner loop have displaced the larger loops formerly in service. The structure

is mounted so as to be rotatable about a vertical axis and fitted to the fuselage or centre section of the wing in the case of a biplane. Owing to the difficulty of correcting for quadrantal errors, the position in which such errors are least is chosen. Remote control is included if this entails a location inconvenient for direct operation. Retractable loops which can be withdrawn in the machine when not in use are also used. The icing-up of rotatable outboard loops has proved another problem. Icing increases the drag and renders possible the fracture of the support, as well as the liability to jamming, so that the unit is put out of action. The difficulty of providing any sort of de-icing device for unprotected outboard loops has led to the design of a small loop in a stream-lined casing which can be freely rotated so as to eliminate the icing trouble.

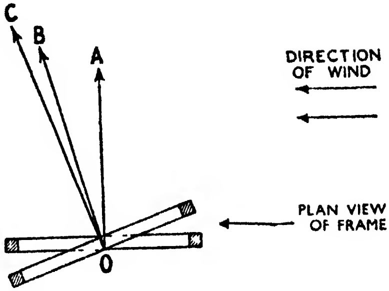


Fig. 10.—Illustration of Method of employing Rotatable Coil to utilize Signals from an Off-Course Transmitter and to correct for Drift.

OA Direction of destination.
OB Off-course transmitter.
OC Offset course for drift.

Quadrature Errors

In installations having rotatable loops to determine bearings as well as homing, errors result from disturbances caused by the disposition of the metal structure, re-radiation, etc. These errors may be quadrantal, i.e. change sign in alternate quadrants or even octantal and are analogous to those which the iron structure of a ship produces on the magnetic compass.

They are considerably reduced by suitable selection of the point at which the frame aerial is fixed and by auxiliary balancing circuits. The residual errors are corrected by the use of an error curve previously plotted from observation of known bearings and subsequently applied to all readings.

VISUAL INDICATORS.

To relieve the operator of the tedium of aural detection, several types of visual indicators or " radio compasses " are available.

Meter Type

The amplifier output circuit may be fed to a full-wave rectifier connected to a zero reading microammeter, while a motor-driven commutator serves to reverse both aerial and instrumental connections in synchronism. When the machine is on course, the succeeding impulses through the instrument are equal and opposite and there is no deflection. If the machine strays from its course, the pulses through the indicator are still alternating but unequal in magnitude, so that the instrument shows a deflection to one side or the other corresponding to the machine's deviation. The R.C.A. Co. have used a dynamo-meter form of indicator, consisting of a wound stator and rotor.

A transformer connected to a low-frequency supply feeds the stator coil, and A.C. from the same source is injected into the frame aerial, the ends of which are connected to the grid circuit of two valves in push-pull. When no signal is received, these valves conduct in turn to an equal extent, and the amplified output being in phase with the stator field of the indicator results in no deflection.

When the machine is off-course, one valve passes more current than the other during its conducting half-cycle, according to the phase of the received signal, and thus gives a corresponding out of balance current through the rotor of the indicator.

Neon Tube Indicators

Another kind of visual indicator used in the standard type homing receiver consists of two neon tubes of the tune-on class, as generally employed as visual tuning devices in broadcast radio receivers. Normally, the two tubes are operated under conditions which produce a visible discharge of about half the length of the tube. Deviation of the aircraft from its course causes the glow path to lengthen in one tube and shorten in the other. This type of indicator is free from mechanical inertia, and it is claimed to be less affected by Morse transmission and atmospheric disturbances. Combinations of visual indicators are employed to show sense as well as bearing readings.

Cathode-ray Tubes

Recently there has been a tendency for existing forms of indicator to be displaced by the cathode-ray tube. Visual indication of signal strength, phase, direction or frequency can be shown by the path traced out by a spot of light on a fluorescent

screen. The chief advantages are (1) Since the indication is given by the deflection of an electron beam, the instrument is devoid of mechanical inertia so that voltage variations at radio frequencies which no aural or dial meter could distinguish can be depicted without much difficulty. (2) Since deflection of the spot can take place in two co-ordinate directions, the relation between two variables can be shown simultaneously.

Direction-finding systems which incorporate the cathode-ray tube are dealt with later in this chapter, and a description of the cathode-ray tube and its uses will be found in Chapter XXII.

GROUND DIRECTION-FINDING BEACONS

Beacons are, in effect, "wireless lighthouses" and operate automatically. They were originally intended for transmitting non-directional signals for use with loop receivers carried in ships, but have proved equally successful for aircraft navigation. The directional transmitting beacon has since been developed and is now extensively used in various forms.

Rotary Beacons

The rotary loop type of transmitter beacon enables the bearing of the ground station to be communicated to aircraft or ships which have no D/F apparatus. Neglecting polarisation errors, for which corrections can be made, the principles are illustrated best in the case where the station transmitter consists of a large loop carrying high-frequency current and rotating at a uniform speed on a vertical axis. The transmitting station sends out a distinctive signal when the loop passes through the meridian. The period of the beacon's rotation, if not known, can be observed from the interval between successive meridian signals (say t_1 secs.). At the instant of receiving one such signal, the operator starts a stopwatch which he stops when zero signal strength reaches his direction (say t_2 secs.). This time as a fraction of the time of a complete revolution enables the bearing to be determined, $\left(\frac{t_2}{t_1} \times 360 \text{ degrees}\right)$. The fact that a relatively long period must elapse before an operator can determine his position by observations from two such beacons has restricted the development of this type of control.

Another form of rotary beacon in which operation does not necessitate constancy of speed of rotation is the type in which the

characteristic signals transmitted change with the direction of transmission. If a predetermined series of signals corresponding to the direction of transmission and characteristic of the particular beacon is known to the observer ; the latter has only to determine the type of signal received when the intensity is a maximum in order to find its bearing. Relatively unskilled operators can take observations on this system with little risk of error.

Course-setting Beacons

Beacons consisting of two loops set at an angle to one another and keyed alternately with interlocked signals, such as the Morse letters A and N, have been developed in America. They enable the pilot to follow a pre-set course along an equisignal zone and reach the beacon without any other form of direction indication. The interlocked signals appear as a continuous dash along the line of equal radiation from the two loops. Improvements on the original designs made with the object of eliminating errors in aircraft with unsymmetrical aerials employ suitable phased vertical radiators.

The equisignal directions need not be at right-angles. The addition of an open aerial at the transmitter enables these directions to be pre-selected so that any area of territory can be interlaced with such paths from existing beacons.

To assist the pilot in determining which quadrant he is in, the N signals are assigned to the quadrant in which the true North lies, and the signal sequence is interrupted periodically by special identification signals, first in the N quadrant and then in the A quadrant, and from the relative intensities the quadrant can be identified.

This type of direction indicator has advantages for heavy traffic lanes when supplemented by marker beacons en route and avoids congestion of requests for bearings in bad weather, but is liable to give trouble from fading, and without D/F apparatus the pilot may be misled if he gets seriously off course. This system has not been used in England.

Improved Systems

Null signal course indications have several drawbacks. When off course, the plane may be uncertain as to which side of the correct track it lies and how far it is away from it. Schemes have been devised to eliminate these uncertainties and convey more complete information to the aircraft.

In one of these, two vertical aerials are used at the beacon with a phase shifting device, the effects of which are to swing the zero signal direction at a uniform rate through a small horizontal angle. The modulated signal is altered instantaneously as the swing takes place in one direction across the centre line.

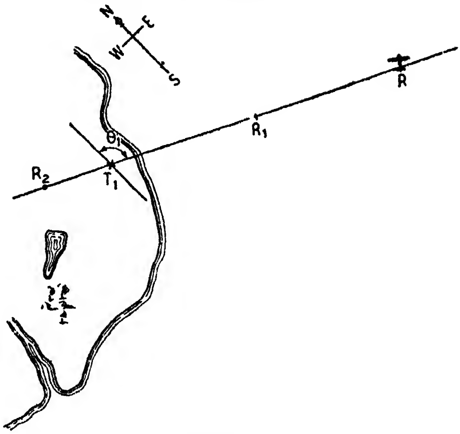


FIG. 11.—T_1 GROUND STATION WITH DIRECTION-FINDING EQUIPMENT. R PLANE WITH ORDINARY RECEIVER. ONLY THE ANGLE θ_1 CAN BE DETERMINED BY BEARINGS FROM ONE GROUND STATION.

Another system involves a pair of rotary beacons turning at a pre-set variable speed. One sends out dot and the other dash signals, and the speed of rotation is such that the minima intersect on the plane's course.

When off course, the plane receives signals of which one train is more intense than the other according to its deviation in position from the normal course.

Television Beacons

Television principles using the cathode-ray tube have been employed for beacon transmission. The station identification sign and the portion of the scale attached to the rotating frame of the transmitter, which shows its orientation with respect to North at any instant, are transmitted as picture signals simultaneously and can be viewed directly on the scale of the cathode-ray tube at the receiver station.

POSITION FINDING.

An aircraft or ship with ordinary receiving equipment but without a D/F installation can find its bearing but not its position with respect to a transmitting station equipped with D/F apparatus.

Suppose the observer is at a point R with respect to a D/F station T_1 (See Fig. 11). When he calls for a bearing, the operator at the transmitting station can determine the bearing Θ_1 from the signals received and will radio this information back to the observer who is then aware that his position is somewhere on the line through T_1, making an angle Θ_1 with true North. It may

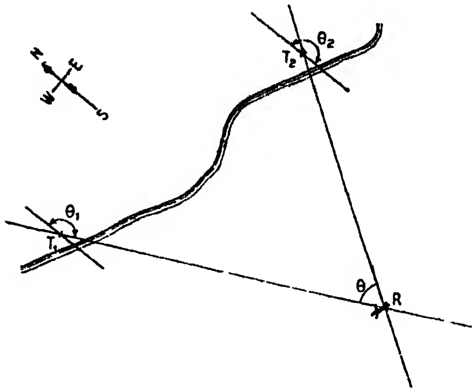


FIG. 12.—LOCATION OF PLANL DEILRMINED BY A FIX FROM BEARINGS OF TWO KNOWN GROUND STATIONS. NO CONFIRMATORY READINGS AVAILABLE.

equally well be at R_1, R_2, or any other point on this line, and the location cannot be defined any closer from the bearing from a single station.

To determine his position the observer of the plane or ship must receive similar information from a second known D/F station, say T_2. The fact that the bearing from this station is Θ_2 determines the line T_2R, whence the point of intersection, subject to observational and other errors, locates the position, and is determined by the operator in the aircraft or vessel. This is known as a " fix." If stations T_1 and T_2 are in telephonic communication with each other, one of them, on receiving a call from the observer, can request the other to take D/F readings of the observer's position. The two bearings being thus known, the " fix " can be located by plotting the lines R_1R and T_2R at one of the transmitting stations. The complete information as to the position of R can then be radioed to the aircraft or ship. (Fig. 12).

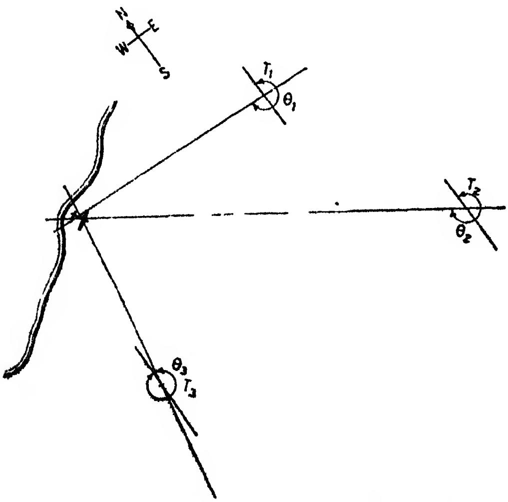


FIG. 13.—CONFIRMATORY INDICATION OF ACCURACY OF A FIX FROM A THIRD GROUND STATION.

Errors

All readings are subject to some error, and the accuracy of location is greatly reduced if the angle Θ is very acute or very obtuse. Since it is

usually not possible for the operator to receive bearings from stations where he would like them to be, observations from three or more points are very desirable for confirmatory checks (Fig. 13).

In the case of several stations concerned in a triangulation, rapid exchange of information is essential in order that the "fix" shall not necessitate considerable correction to allow for change in position which has occurred during the interval between taking bearings and completion of the computation.

As the probable error in reading any bearing is generally known, a systematic process of averaging the readings enables the final location to be determined within known limits of error.

PULSE-MODULATED SYSTEMS

Pulse-modulated navigational systems were developed both in Great Britain and America during the late war. The British system is known as "Gee" and was intended primarily for aircraft purposes, but has also been used extensively for ship navigation.

The Loran, or American Long-Range Navigational Aid, is similar basically to Gee, but operates on a longer wavelength and has a greater range under most conditions.

Basic Principles

The operation of both systems is based on determining the difference in the time of arrival at the receiver of radio-frequency pulses transmitted simultaneously or at definite intervals from a series of ground transmitters.

The Gee system, as it is known to many thousands of aircraft navigators, depends on the use of hyperbolic or lattice charts. The reader who is directly familiar with the mathematics of conic sections will readily understand the basic principles of these hyperbolic charts. Such readers are asked to forgive the present digression which is designed to give the non-mathematical reader a general idea of the principles involved.

Two stations A and B are "synchronised" so that they can send out pulses at the same instant; it is obvious that if the aeroplane is equidistant between the two stations, the pulses will be received by the aircraft radio at the same instant. If the aeroplane is nearer to station A than station B, the pulse from A would be received a fraction earlier than the corresponding pulse from B. This difference in time represents the difference in distances from the two sending stations; in other

words, the pilot can deduce from the indicator screen that he is, say, two miles nearer to station A than he is to station B.

Hyperbolic Charts

So far the scheme suggested is quite practicable, but it does not yet solve the problem of fixing the position of the aircraft. The hyperbolic charts provide the missing link. When the ancient Greeks (200–300 B.C.) studied conic sections—i.e. the various curves obtained by cutting a cone in different ways—they can hardly have imagined that their discoveries would be applied with such success in the twentieth century.

Since the Greeks discovered the hyperbola, mathematicians have given much time to studying its properties. As a result they have discovered that this curve has a peculiar property which renders it extremely useful for solving the above-mentioned problem of fixing the position of an aircraft under the conditions given.

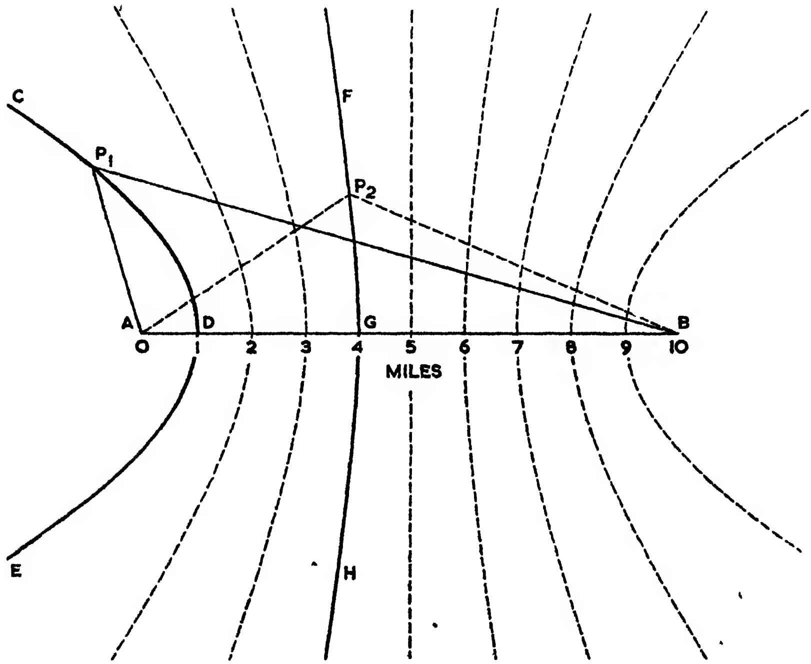


FIG. 14.—PRINCIPLE OF THE HYPERBOLA.
For any point, say P_1, on the hyperbola CDE, the distance P_1B minus the distance AP_1, will always be 8 miles (*i.e.* the difference factor). Similarly, for any point P_2 on the hyperbola FGH, the difference factor will be P_2B minus AP_2, namely, 2 miles.

This property is expressed as follows:

Any point on a hyperbola has a *fixed difference in distance* from the two focii. Referring to the diagram in Fig. 14, if A and B represent the two focii or sending stations, say ten miles apart, if we draw a hyperbola from position 1, which is distant one mile from A and 9 miles from B, every point on that hyperbola will have a difference of eight miles in its distances from A and B.

Similarly, if we draw a hyperbola through the position 4, which is four miles distant from A and six miles distant from B, the difference factor for all points on this curve will be two miles.

Hyperbolic charts of this kind are prepared for each pair of stations and can be shown on a diagram as in Fig. 15. If, after taking his first reading, a navigator in an aeroplane at the point P

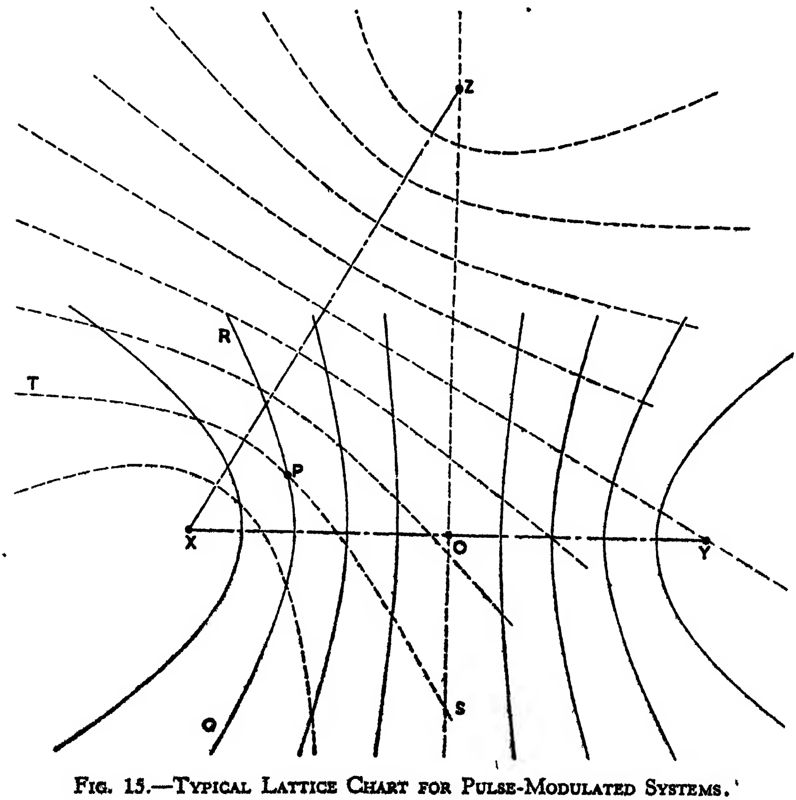


FIG. 15.—TYPICAL LATTICE CHART FOR PULSE-MODULATED SYSTEMS.

finds that his difference factor for transmitting stations X and Y is, say, fifty miles, he can tell that his position is somewhere on the hyperbola R.P.Q.

If a third transmitter Z, suitably disposed in relation to the transmitters X and Y, is also sending out simultaneously synchronised pulse signals, the observer is able to obtain a further position line, in a similar way, by measuring the difference in time between signals arriving from, say, transmitters X and Z. Therefore he can deduce that his position will also lie on the line TPS and his actual position with relation to the three transmitters will be where the two lines, or hyperbolæ, intersect.

Suitable charts to facilitate position plotting can be drawn, consisting of a series of hyperbolæ, each representing a known difference in distance between the three transmitters, and these charts can be superimposed on a map of the area served. On this account, the Gee and Loran systems are also termed hyperbolic or lattice systems.

The Gee System

In practice the Gee system consists of a chain of transmitters arranged in groups of three or four, the transmitters being located about seventy or eighty miles apart.

Each transmitter operates in the same radio frequency, usually between 20 and 80 Mc/s (3·75 and 15 metres), and is continuously emitting synchronised radio pulses. A master transmitter is used in each group to control the pulses of the subsidiary or slave transmitters, crystal controlled timing being employed.

The aerials are omni-directional and the use of the very high frequencies result in the reception of ground waves only, thus eliminating reflection troubles normally associated with the lower frequency wavebands. They have, however, the disadvantage of optical range and signals may be seriously impaired if the optical path between the transmitter and the receiver is obstructed.

Equipment

The equipment carried by a ship or aircraft for the operation of the Gee system consists of a receiver and an indicator of the cathode-ray display type.

In operation, the pulses received from the three or four transmitters can be received and displayed simultaneously on

the screen of the cathode-ray tube and the arrangement permits the time difference of arrival of corresponding pulses from each transmitter to be determined to within a millionth of a second.

Range of the Gee System

Satisfactory reception of the transmitted pulses over sea can be obtained up to 100 miles, but, in practice, reasonable results have been achieved at ranges of 150 miles.

For aircraft the range depends on the nature of the land between the aircraft and the transmitters, and also the flying height of the plane. Reception is normally quite satisfactory up to 400 miles at 15,000 feet and up to 200 miles at 5,000 feet.

The Loran System

As we have already mentioned, this system is based on the same principles as Gee, but operates on a radio frequency of approximately 1900 kc/s (157 metres).

Much greater ranges are possible with Loran as it takes advantage of the increased range of the ground waves at the lower frequencies, and is not so readily affected by height. There are, however, other troubles introduced which are peculiar to the short and medium wavelengths, e.g. although the range of the Loran system may be twice as far by day as that obtained with Gee when operating over sea, it may not be as good over land, as a certain amount of ground absorption may occur.

At night Loran waves are readily reflected by the upper atmospheric layers and its range thereby considerably increased, with the added difficulty for the observer of distinguishing between the direct and the reflected wave.

With Loran, only two transmitters are operated in synchronism, a master and a slave which may be spaced up to 600 miles apart. Signals from the master transmitter are received at the slave transmitter and are relayed by the slave after an accurately controlled time delay. To obtain a definite fix the observer has to take readings from two pairs of transmitters and the deductions are read off from lattice charts in a manner similar to the Gee system.

Equipment

The equipment, as for Gee, consists of a suitable receiver and cathode-ray indicator, but more skill in operation is required to distinguish between the direct and reflected rays, as both will appear on the screen.

Range of Loran

A range of about 700 miles by day over the sea can be obtained with this system and twice this distance by night. This range is considerably reduced for the direct wave over land, especially over rough ground, but the reflected wave is, of course, unaffected by the nature of the terrain and ranges of 300 to 1,200 miles may be obtained over land at night.

Conclusion

It should be borne in mind that research work in this field is continually in progress and the details of the pulse modulated systems mentioned in this chapter are only intended to convey a general idea of the principles involved. Such items as range, wavelenths and equipment employed may vary considerably as the result of improvements effected by this research.

The method of determining the time difference in arrival of the radio-frequency waves at the receiver is not confined to the use of synchronised pulses. For instance, by using continuous or continuously modulated waves transmitted by two or more synchronised stations it is possible, with suitable equipment, to measure the phase difference between the respective waves on arrival at the receiver. Thus the difference in time taken for each wave to reach the receiver, and, therefore, the difference in distance between the receiver, and the transmitter can be calculated. The use of lattice charts is also applicable to this method.

The subject of Radar is dealt with in the following chapter, but it should be mentioned here that many of the larger vessels now carry this equipment as a navigational aid for local or inshore navigation. It provides a safe passage at normal cruising speeds under conditions of poor visibility as the position of the vessel with relation to buoys, shore-lines and navigation marks is indicated on the cathode-ray tube display, together with the location of neighbouring vessels or obstructions.

CHAPTER XXVI

A SURVEY OF RADAR

RADIO detection and Ranging (Radar) is the art of locating the presence of objects by radio means, determining their angular position, with regard to some reference point (Relative bearing) and their range. In order to accomplish this, a beam of R.F. energy is directed over some given area in search of a target, by means of a highly directional rotatable aerial. If the beam strikes a target some of the R.F. energy is reflected and a small portion of this reflected energy travels back in the direction of the transmitter.

If a sensitive receiver, capable of detecting this reflected energy is arranged to operate in the vicinity of the transmitter, together with some time measuring device, capable of measuring the extremely short periods of time elapsing between transmission of the energy and reception of reflections (Echoes), the following information can be deduced when echoes are obtained.

(1) Some reflecting body (in Radar terminology " a Target ") has been found by the beam, as demonstrated by the echo received at the receiver and recorded by the time measuring device.

(2) It can be shown that the range or distance of the target from the transmitter is proportional to the time interval, measured from the instant that transmission of energy commences, to the instant at which the returning echo is received.

(3) The bearing of the target, measured with reference to the direction of the ship's head, or in the case of a shore station, measured from compass North, is indicated by the angle through which the aerial must be rotated, in order that the centre of the beam may face the target. This is evidenced by the fact that an echo is received and recorded only when the aerial is rotated, so that the beam covers the target.

(4) The elevation or height of an airborne target can be obtained, under favourable conditions, by measuring the angle of elevation by which the aerial must be tilted in order that the centre of the beam may face the target, and by simultaneously measuring the slant range thus obtained, The slant range as indicated in Fig. 1 is measured in the same manner as a normal range as described in sub par. (1).

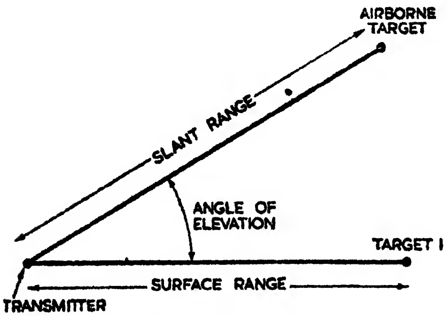


FIG. 1 —TARGET HEIGHT MEASUREMENT.

Requirements for the Basic Radar System

The minimum requirements for the basic Radar system are therefore:

(*a*) A suitable transmitter.

(*b*) A very sensitive receiver.

(*c*) A device capable of measuring short intervals of time of the order of a microsecond or less.

(*d*) An aerial system having highly directive properties and capable of being rotated through any desired angle. If designed for use against airborne targets it must be capable of being tilted to an extreme elevation of at least 45 degrees.

An essential *condition of operation* is that the transmitter and receiver must be arranged in such a manner that received echoes can be readily identified with the individual transmissions from which they result. This is necessary in order to enable the measuring device to discriminate and measure the time interval between each transmission and the reflections resulting therefrom. This requirement implies the necessity for the introduction of a co-ordinating or timing function.

The above conditions are satisfied by pulsing the transmitter so that it generates short, sharp bursts of R.F. of the order of a microsecond or so in duration, with a sufficiently long interval or resting time between each successive pulse to permit all echoes from the extreme limits of the service area time to return before the commencement of the next pulse. Also the measuring device must be arranged to record the time delay between

each transmission and the reception of returned echoes. (See Fig. 2.)

The pulse length, or duration of each pulse (in microseconds), and the rate at which successive pulses are repeated (repetition rate or pulse frequency) are determined in design by the performance and duties which a particular Radar system is required to fulfil.

Historical Development of the use of Radar

A pulsed system was used successfully in measuring reflection of radio waves from the Ionosphere, and it seems that the possibilities of Radar came to be realized as a result of this experimental work.

Serious work on Radar appears to have commenced in this country in 1932 and a great impetus was given to its development by the imminent danger of war. The vital necessity for providing our comparatively small, but efficient Air Force with improved means for obtaining early and accurate information regarding the movements of enemy bomber squadrons was

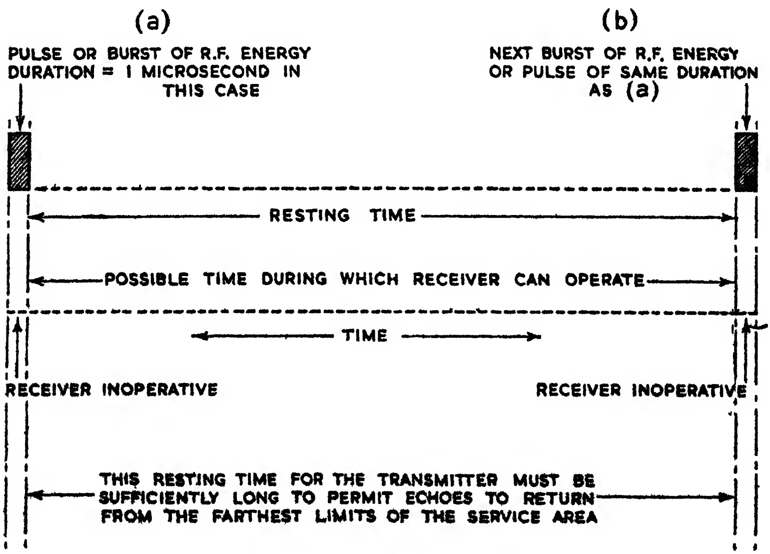


FIG. 2.—RELATION OF PULSE LENGTH TO REPETITION FREQUENCY.

The transmitter and receiver must be arranged so that the echoes can be identified with their transmitted pulses.

realized, and this caused the development of Radar as a possible solution to the problem to be stepped up to a very high level.

In consequence of the intensive research and development work that had been carried out on Radar, when the battle of Britain commenced, Radar ground stations, built and in operation, were able to supply vital information regarding hostile air movements, thereby enabling the Royal Air Force to surprise and destroy enemy raiders in large numbers. A milestone in the development and application of airborne Radar seems to have been the successful operation of locating the *Altmark,* lurking in a Norwegian fiord, with an early type of Radar installed in a suitable plane for this purpose.

About the end of 1940 and early in 1941 Radar was being extensively employed in night fighting operations. Directed by R/T from powerful ground Radar stations, night fighters were manœuvred close enough to enemy night bombers to enable them to use their own short-distance Radar sets (referred to by Winston Churchill as the " smeller "). In this manner, invisible enemy aircraft could be located and brought to action.

In the meantime the Navy had been very busy indeed and had learnt much about the technique and application of Radar to its own particular problems. These were mainly concerned with : (1) Search sets to give early warning of the approach of enemy airborne and surface craft. (2) Range finding sets for " Fire control " (gunnery) and (3) The application of Radar principles to navigational aids and the never ceasing hunt for the " U " boat.

An example, typical of the high state of perfection reached by Naval Radar, is the occasion on which Admiral Sir Bruce Fraser, in the *Duke of York,* watched the echo vanish as the fog-enshrouded *Scharnhorst* gradually disappeared below the waters of the North Atlantic. This occasion was also distinguished by the efficiency with which the *Scharnhorst* was tracked by Radar. In the final phases fire was opened upon the *Scharnhorst* by the guns of the *Duke of York* under Radar direction, the German commander, at that time being unaware that the *Duke of York* was even within range of him.

Since then German witnesses have testified at Nuremberg to the important part played by airborne Radar in winning the

battle of the Atlantic—and the final defeat of the " U " boat menace.

The Merchant Navy has also paid its tribute to the effectiveness of Radar for convoy work and as a navigational aid.

Classified Applications

These examples serve to show that Radar applications can be generally classified under the following headings :

(*a*) *Radar Sets for Long Range Warning and Search.*—Fixed shore stations or mobile ship stations fitted with these sets keep a constant watch, and search some specific area continuously, in order to give early warning of the approach of hostile aircraft or surface craft. The major requirement for this class of set is maximum range.

(*b*) *Fire Control or Gunnery Sets.*—Radar sets installed for this purpose must be capable of measuring range, bearing and/or elevation with great accuracy. In general, these sets are designed for a degree of precision in measurement which is not practicable for long-range warning sets.

Fire control, or gunnery sets, generally come into action after hostile craft, previously reported by long-range warning sets, have closed to some considerably shorter range.

(*c*) *Airborne Sets.*—Light, portable equipment is used by patrol aircraft when searching for enemy targets. The equipment may be designed to detect other aircraft, surface vessels or submarines. The Radar equipment may also be used in such cases as an aid to navigation to determine course or position with reference to a home based beacon.

It is known that American Radar fitted in aeroplanes based on the Aleutian Isles enabled these aircraft to operate almost continuously in that region of frequent fogs and low visibility.

The Aleutian Archipalego is studded with islands which rise abruptly to great heights, directly from sea level. Without the aid of Radar to give warning of these navigation perils, air scouting and patrolling in the Aleutians would have been impossible during the prevailing long periods of fog and low visibility.

The main requirements for airborne equipment are that it should be light and compact, and within limits sets must be designed for maximum range, definition, and/or precise measurement according to their particular application.

(*d*) *Radar Beacon Stations.*—These are generally small, compact transmitter-receiver sets, in which the receiver may be actuated by Radar transmission from a ship to cause the beacon transmitter to radiate Radar signals. This transmission is treated as an echo at the calling station, where it is measured in the normal manner for range and bearing.

Radar beacons of this type were employed with great success to enable our supply ships to navigate the Scheldt in foggy weather and under conditions of low visibility. This feat of navigation, with the aid of Radar became normal practice.

The peace time future of Radar has not yet been fully explored. It seems very likely however, that it will become a valuable aid to navigation for the Merchant Navy and Civil Aviation, and a noteworthy contribution to the safety of all travellers by sea and air.

Radar systems employing frequency modulation and C.W. transmission have been developed, but at the present time the pulsed system is employed almost exclusively.

The Use of the Cathode Ray Tube

It has already been stated that pulsed Radar systems measure range or distance in terms of *time*. This is made possible by the development of the cathode ray tube as a device for measuring very short periods of time and by the knowledge that all ether waves travel in free space with a velocity of 186,000 miles per second or 328 yards per microsecond (approximately).

It is evident that the energy reflected from a target travels back in the direction of the transmitter with the same velocity as the transmitted wave travelled outwards to the target, consequently the time taken for the reflected energy to travel back from the target is exactly half the time elapsing between the commencement of each pulse of transmitted energy and the return of the echo.

For its Radar application the cathode ray tube is arranged to measure the full time interval, but it is calibrated to give a reading of 164 yards to the microsecond. In other words each microsecond of time interval recorded by the cathode ray tube means that energy has travelled outwards to a target 164 yards distant from the transmitter and that the echo has travelled 164 yards back again, making a total of 328 yards per microsecond for the outward and return journey.

The range calibration of the cathode ray tube can therefore be expressed as:

Range =

$$\frac{\text{Observed time for outward and return journey}}{2} \text{(microseconds)}$$

multiplied by the velocity of ether waves in free space (328 yds. per microsecond).

$$\text{Range (yds.)} = \frac{\text{Observed } time \text{ in microseconds} \times 328}{2}$$

= 164 yds. per microsecond.

This is the fundamental *time-range* relationship which is used to calibrate the cathode ray tube.

The actual calibration of the screen of the cathode ray tube can be considered in two steps:

Step 1.—The length of the diameter of the screen is calibrated by a time base generator which produces a deflecting voltage causing the electron beam to trace a fluorescent line across the diameter of the screen of the cathode ray tube in some given time. This makes the length of the diameter of the screen proportional to the time required for full deflection, a given deflection time is therefore *determined by the rate at which the time base voltage rises and so causes the bright line to be completely traced.* For example, suppose that the *time base* circuits are adjusted so that the rate of the voltage rise causes the electron beam to sweep out a line of *trace* across the diameter of the screen in, say, 1,000 microseconds. This makes the length of the trace proportional to 1,000 micro-seconds (one millisecond).

Step 2.—Since 1 microsecond is the time required for an echo to be returned from a target 164 yards distant from the transmitter, the trace across the diameter of the screen in the above circumstances becomes proportional to 164,000 yds., (i.e., 164 × 1,000).

The simplest method of subdividing this trace, although not very accurate, is to place a transparent scale over the screen of the cathode ray tube, thus enabling intermediate distances along the trace to be read off directly from the transparent scale. (See Fig. 3).

We now have a means of measuring by interpolation very short fractions of time, and because of the *time-range* relationships explained above, we can also calibrate the line traced by

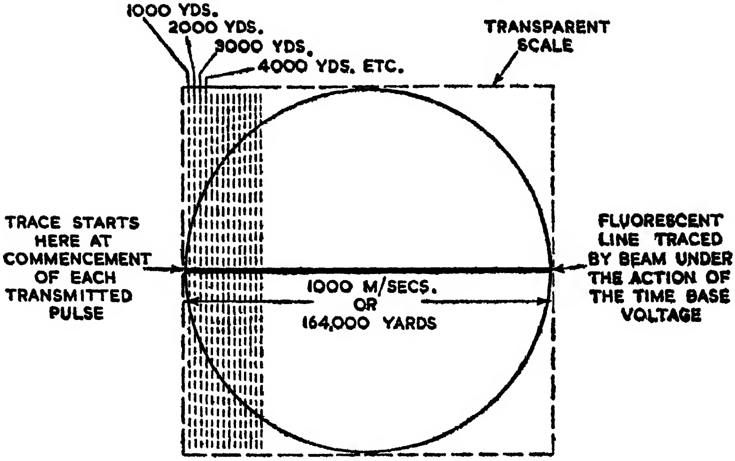


FIG. 3.—CALIBRATION OF CATHODE RAY TUBE SCREEN
This is achieved by means of a transparent graduated scale, placed over the screen.

the time-base to read 164 yards of range for each fraction of length proportional to a microsecond.

Before passing to the next step it should be noted that by increasing the speed of the time-base sweep, i.e., the rate of rise of the deflecting voltage, we can make the same length of trace proportional to a smaller period of time. Thus, if the time-base voltage is adjusted to sweep out the trace in say—50 microseconds, the trace length becomes proportional to 50 microseconds, and by substituting the *time-range* equivalent, it also becomes proportional to $50 \times 164 = 8{,}200$ yds. The subdivisions indicated by the transparent scale must now represent proportionally smaller values.

To sum up, it can be said that by adjusting the speed of the time base we can make the total trace length proportional to any desired period of time and therefore proportional to any desired range. Intermediate readings of time or range along the trace are in the same proportion to the total time or range as the subdivisions are to the total length of the trace.

In the simplest form of application, (i.e. the "A" display) the "X" or horizontal deflection plates of the cathode ray tube are used for the time base voltage which must be applied to cause the electron beam to sweep out the trace across the screen. The output of the receiver is applied to the "Y" or vertical deflection

plates. The result of this arrangement is that whenever an echo is received the output of the receiver applied to the " Y " plates causes the trace to be deflected upwards—vertically—for the duration of the echo. The effect of this is to produce a " pip " in the time base line or trace thereby recording the length of the trace at the instant the echo arrived.

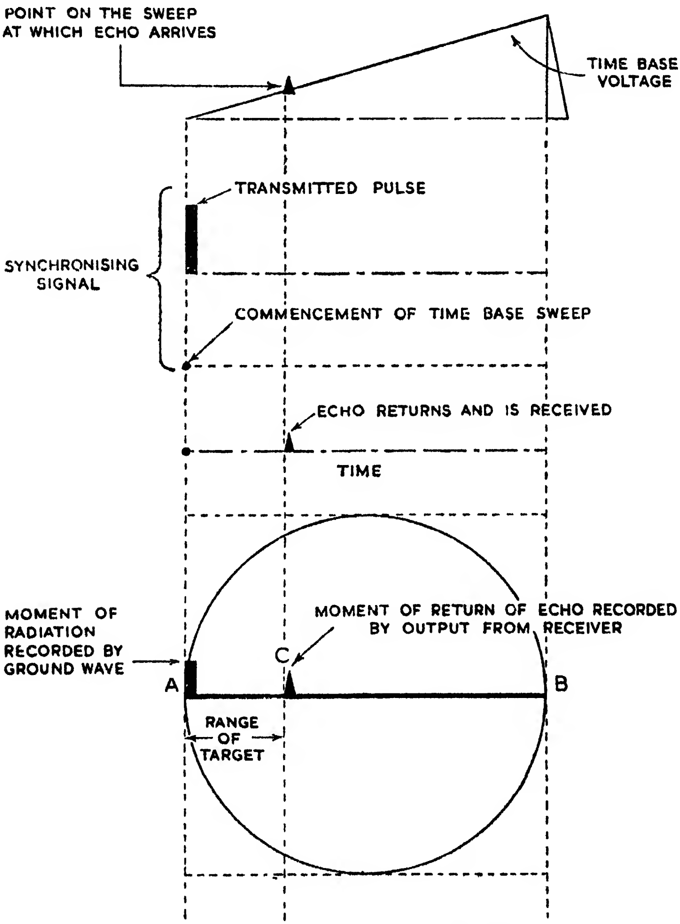


FIG. 4.—CALIBRATION OF TIME BASE.

If AB has been made proportional to, say, 100,000 yards

$$AC = \frac{\text{Length AC}}{\text{Length AB}} \times 100{,}000$$

AC in above example = 25,000 yards.

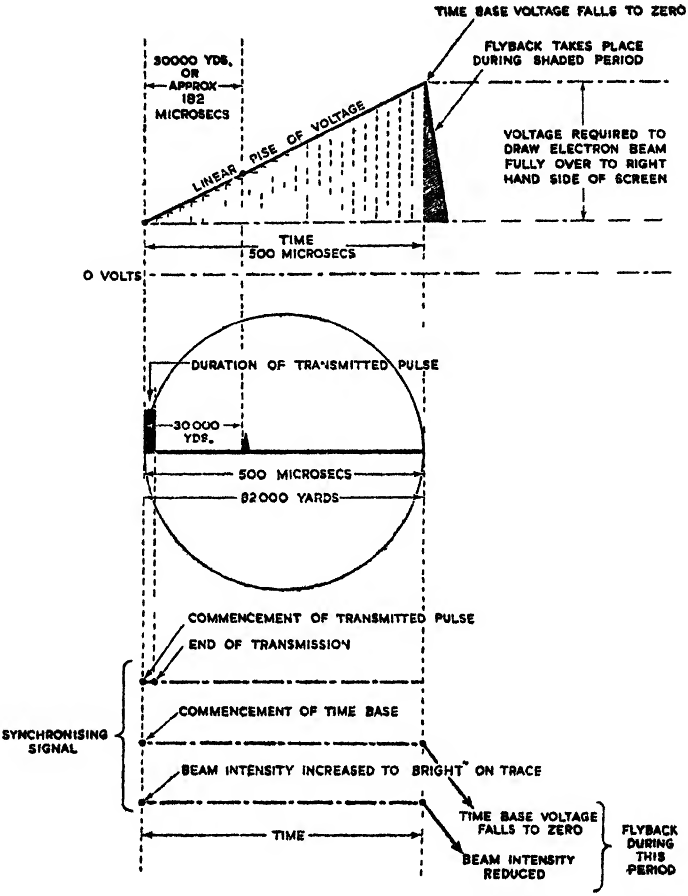


FIG. 5 —RELATION OF RANGE TO FORM OF TIME BASE VOLTAGE WAVE.

This example shows
Sweep Time for Time Base – say, 500 microseconds – 500 × 164 yards = 82,000 yards
Range of Target – say, 30,000 yards

If now we introduce a co-ordinating or *synchronising* control, such that it causes the *time base generator to commence each successive sweep at the instant that each pulse of transmitted energy* is radiated, a definite relationship is established between the instant of transmission of the energy and the instant of return of the echo, with this arrangement, the range of any target can be read

off the calibrated scale, since the position of any pip along the trace, measured from the commencement of the trace is proportional to the *time which has elapsed between the commencement of the transmitted pulse and the receipt of the echo* (see Fig. 4).

Time Base Voltage

The form which the time base voltage wave must take in order to produce the kind of trace required is shown in Fig. 5. Inspection shows that it is a linear rise of voltage, rising from the constant voltage value which is required to position the beam at the left hand side of the screen (looking front), to that value of voltage which is required to deflect the beam across to the right hand side of the screen, the maximum value of this voltage is constant, but the rate at which it rises controls the speed of the beam across the screen and therefore the *time* to which the trace is made proportional.

It is important to note that this rise of voltage must be as nearly linear as possible. This means that the beam must move equal distances in equal time, consequently, the voltage must rise by equal amounts in equal times. If the voltage rise is appreciably non-linear, intermediate readings along the trace will not be equal for equal subdivisions of the transparency scale.

It will be seen from Fig. 5 that at the end of each sweep, the time base voltage falls very quickly to zero, in consequence of which, the beam is returned to the left hand side of the screen again by the positioning voltage in readiness for the next sweep. The commencement of the next sweep is timed by the synchroniser to start at the same instant that the next pulse of R.F. is generated.

Dimming

It is obviously undesirable that the return of the beam to the left hand side of the screen (the flyback) should be visible on the screen for two reasons :

(*a*) It would confuse the observer.

(*b*) It would cause echoes to be registered from targets outside the maximum range for which the screen has been calibrated by the time base speed adjustment.

In order that the flyback may take place in darkness, therefore,

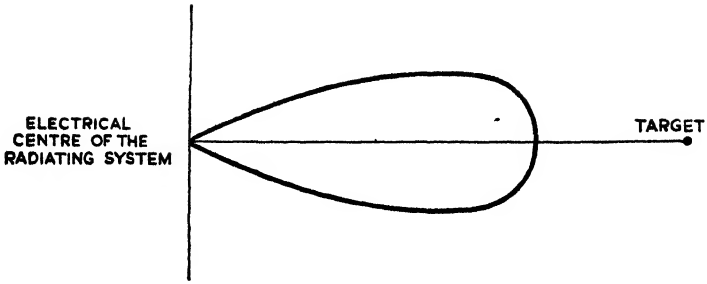


FIG. 6.—AERIAL ON TARGET.

the general practice is to arrange matters so that the synchroniser causes the electron beam to be brightened only at the beginning of each sweep and to be dimmed almost to the point of extinction at the end of each sweep. Thus at the commencement of each transmitted pulse two separate actions take place simultaneously in the cathode ray tube.-

(1) The time base generator is started in order to commence sweeping out the trace.

(2) The electron beam is intensified for the period of the sweep. At the end of each sweep the deflecting voltage falls to zero, the intensity of the electron beam is reduced to near zero, and the flyback takes place in darkness.

There is also another important reason for dimming between the end of one sweep and the beginning of the next. For a small period of time at the end of each sweep, the beam is momentarily stationary at the right hand side of the screen and when returned to the left hand side it again becomes stationary until the next sweep starts. In the absence of dimming, bright spots would therefore appear at the left- and right-hand sides of the screens and in addition to being undesirable they would also tend to cause burning of the fluorescent coating at these points.

Measurement of Bearing

The bearing of a target may be stated as a "true" bearing with reference to Compass North or as a "relative" bearing (i.e. with reference to the direction of a ship's head). A repeater operated by the ship's compass is usually installed in the Radar office and an indicator is also provided to show the

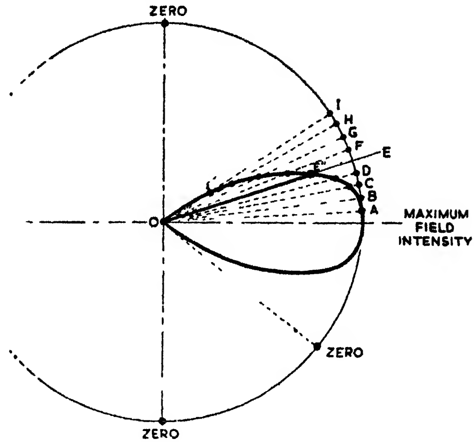


FIG. 7.—DEVELOPMENT OF A TYPICAL RADIATION PATTERN.

The figure in heavy line is the pattern obtained by plotting observed readings A to I, etc. (taken on the circumference):—against angles AOB, AOC, etc. If the observed field strength at Max. = say 100 micro-volts, the field strength at I in the circumference is $\frac{OI''}{Max.} \times 100$. Similarly, the field strength at E on the circumference is $\frac{OE''}{Max.} \times 100$, and so on.

instantaneous angle which the aerial makes with the ship's head as it is rotated by the operator. The aerial is said to be on target when a line drawn through the electrical centre of the aerial passes through the target (see Fig. 6).

This condition is indicated in the very simplest case by the amplitude of the echo appearing on the screen of the cathode ray tube. The aerial is rotated until the desired echo appears with maximum amplitude, the relative bearing is then read off and this can be translated into true bearing by comparison with the compass repeater.

The radiation patterns of an aerial are usually shown by figures of the form shown in Fig. 6, and since radiation takes place in three dimensions it is usual to show separate patterns, or figures for the vertical and horizontal planes respectively.

The figure describing the horizontal radiation pattern of an aerial can be obtained by transporting a receiver round the transmitting aerial in a circle of radius not less than 5 wave-lengths from the aerial (usually more), and measuring the signal strength received at various angles round the circumference.

Measurements are usually taken in terms of milli-volts or micro-volts per metre (height of aerial). If the height of the test aerial and the radius at which readings are taken are both constant, the readings obtained in milli-volts or micro-volts are the field strengths per metre for any given angle measured around the circumference of the circle described in transporting the receiver round the aerial. (Fig. 7).

A maximum field strength will be observed at some point on the circumference which lies directly on a line passing through the centre of the aerial system. The maximum field strength found at this point is taken as 100. Field strengths received at

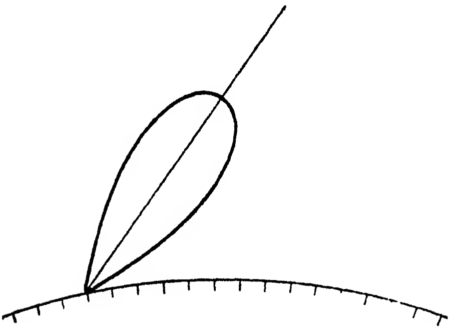


FIG. 8.—RADIATION PATTERN FOR TILTED AERIAL.
In this instance the beam is clear of the earth and elevated to radiate wholly into space.

other points round the circumference are plotted as percentages of the maximum, against the angles of observation. It is important to realize that the figure thus derived is merely a field *pattern* and that it *does not outline the extreme boundaries of transmission* (see explanatory note under Fig. 7).

The vertical radiation pattern can be obtained by turning the aerial through 90 degrees and proceeding as for the horizontal pattern. This gives a result similar to that which would be obtained by flying an airborne receiver round the aerial at different heights. The horizontal pattern indicates the coverage for surface targets and the vertical pattern provides similar information for various angles of elevation, but the latter is true only *as long as the beam is clear of the earth and elevated to radiate wholly into space as in Fig.* 8.

When the vertical radiation pattern and the angle of elevation is such that some part of the beam touches the earth, reflections take place from the earth and the vertical pattern in free space for various angles of elevation is modified by the reflected energy from the earth.

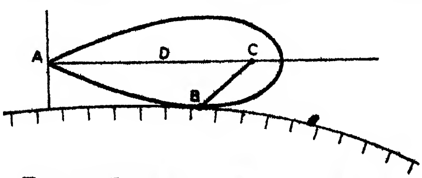


FIG. 9.—REFLECTION WHEN PATTERN IS NOT ENTIRELY IN FREE SPACE.

This is shown in Figs. 9 and 10. The path of the reflected wave A.B.C. is

Fig. 10.—Modified Radiation Pattern due to Reflection.

longer than the direct path A.D.C., wherefore, according to the difference between the lengths of the two paths and the actual wavelength employed, the reflected wave via the indirect path will arrive at C (Fig. 9) either in or out of phase with the wave arriving there by the direct path. If the reflected wave and the direct wave are in phase they add to reinforce the field strength at C. If they are in anti-phase they cancel each other out. If their phases are intermediate between 0 and 90 degrees, the fields must be added together vectorially, in order to find the resultant.

Thus, when ground reflection is present, the vertical pattern or *lobe* for free space is modified by the ground reflections, consequently the pattern shown in Fig. 9 may be modified by reflection to something like that shown in Fig. 10. When the beam touches the earth's surface the height of a target cannot be calculated by measuring the angle of elevation and the slant range; also the maximum range and continuity at which an airborne target can be detected is also adversely effected.

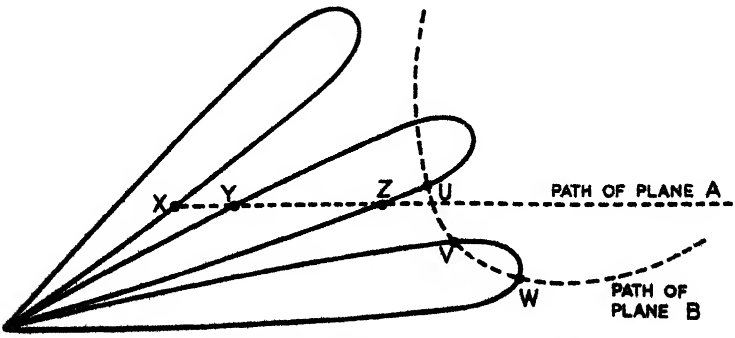


Fig. 11.—Erratic Detectiŏn of Aircraft. (Conditions as in Fig. 10.)

Plane A is not detected until it arrives at Z. It is held until it reaches Y where it is lost until it arrives at X. Plane B is detected at W, held until V, lost at V and detected again at U.

This can be seen by consideration of Fig. 10 and 11. For precision and direct readings of height very narrow beams are therefore desirable in order to avoid the effects of ground reflection, and at the same time to gain the additional advantage obtainable by concentrating radiation of the whole of the R.F. energy into the smallest possible area. Concentration of the R.F. energy into a narrow beam must obviously produce a stronger strike, and a larger echo is therefore returned for any given radiated power.

Beam Widths

Further consideration of the matter shows that beams which are narrow in the horizontal plane are also desirable for accurate measurement of bearing of surface craft or other objects. A narrow beam offers the advantages of increased concentration of energy and better definition (i.e. the ability to pick out and discriminate between adjacent targets). Why, then, are narrow beams not always used? The answer is given below in the following order:—

(1) The width of a beam depends upon the number and disposition of the dipoles and the size and geometry of the reflecting system. In other words, the radiating system, including reflector, must be increased in dimensions when narrow beams are required.

(2) The length of the dipoles is determined by the R.F. carrier frequency employed. For long waves the dipole length must be increased, since $\frac{\lambda}{2}$ dipoles are usually employed in the radiating system.

(3) For long wave systems, therefore, radiating reflectors become very large indeed. They require considerable space when erected, they are mechanically difficult to support and rotate, and the wind resistance becomes very high indeed.

(4) On the other hand, as the wavelength decreases the range obtainable for a given R.F. power output decreases.

Thus the position arises where long range sets for warning purposes must employ comparatively long waves, using fre-

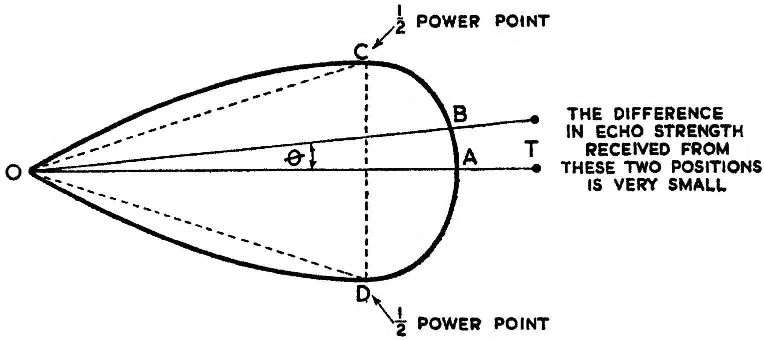


FIG. 12.—BEAM CONSTANTS.

C and D are called half-power points since the field strength at these points is 70·7 per cent. of the maximum OA and because E^2 is proportional to power, i.e. $\left(\frac{1}{\sqrt{2}}\right)^2$

quencies of the order of 100 megacycles and upwards, in order to obtain the necessary range with reasonable power outputs. The beam in this case is, therefore, generally fairly wide—perhaps 20 degrees or more, because at the comparatively low frequencies used for warning sets, radiating systems for narrow beams would become impracticable on account of the dimensions and weights involved.

For the foregoing reasons, therefore, long range warning sets usually employ a comparatively low carrier frequency and a fairly wide beam, whilst short range precision sets make use of ultra high frequencies of the order of 3,000 megacycles and upwards—(10 cms. and downwards) in order to gain the increased precision of measurement inherent to narrow beams, the use of which now becomes possible, but accompanied by a sacrifice in range.

The line of demarcation may be said to start at about 3,000 megacycles, because it is around this frequency that the use of waveguides becomes practicable, and also the dimensions of reflectors suitable for producing narrow beams become small enough for installation, support and rotation in mobile Radar stations.

When wide beams are used it will be seen from Fig. 12 that the *rate of change* of signal strength in the region of the maximum value at "A" is very small indeed. For example, at the angle θ, OB is very little less than OA, which is the maximum value.

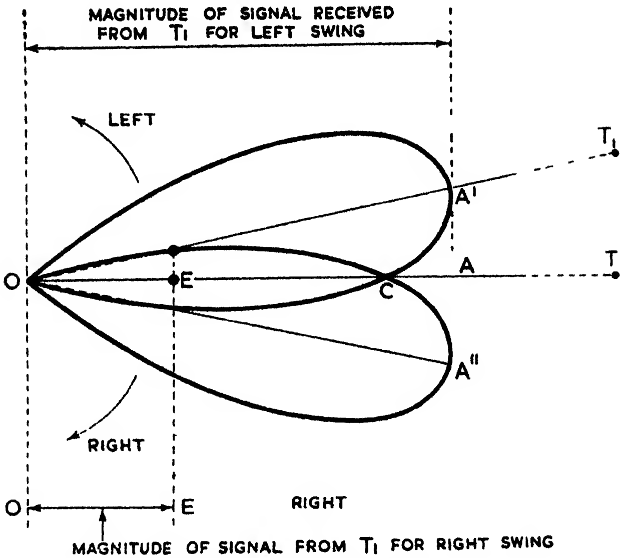


FIG. 13.—BEAM SPLITTING.

Method used to improve accuracy of training with wide beams.

This makes it very difficult to find with precision the exact bearing of a target. Accordingly, a system of beam splitting is used in order to improve the discriminating properties of the aerial system.

Beam Splitting

Further inspection of Fig. 12 shows that the *maximum rate of change* of field strength, which is what we require for discriminating purposes, takes place at points C and D, the field strengths at these points is 70·7 per cent. of the maximum, and they are called the " half power " points of the lobe or pattern.

Assuming that the target " T " is fixed, and that the beam if rotated to right and left of it alternately through the angles AOA^1 and AOA^{11} respectively (Fig. 13), the patterns would intersect at the half power points C. This means that when the lobe is switched to the right the signal from the target will be proportioned to CO, similarly when the lobe is switched to the left the signal from T will also be proportional to CO. In other words, *the signal from T will be proportional to OC if the beam is switched to right or left of the target through this angle.*

Assuming that the aerial continues to swing backwards and forwards through the angle A^1OA^{11}, consider the effect on the echoes received from target T1. When the beam swings to the left, a maximum signal will be received from T1, but when it swings to the right, the signal received from T1 falls to a value proportional to EO which is less than CO. This means that the signal received from T1 will be greater for the left-hand swing than for the right-hand swing. These conditions are exactly reversed for the target at T. The conclusion is, therefore, that *equal* signals from right- and left-hand swings are only obtained when the centre of the aerial system exactly faces the target. When the target is in any other positions relative to the aerial the signals received for right and left-hand swings of the beam are *unequal*. This is the principle generally employed to enable the operator to train the aerial on target when wide beams are used. The field pattern is switched continuously as the aerial is rotated and signals received from right and left lobes are also continuously compared. When *both* positions of the lobe give *equal* signals the aerial is on target.

NOTE.—In this case training is *not* performed by adjusting for *maximum* signal, but by adjustment for *equal signals*.

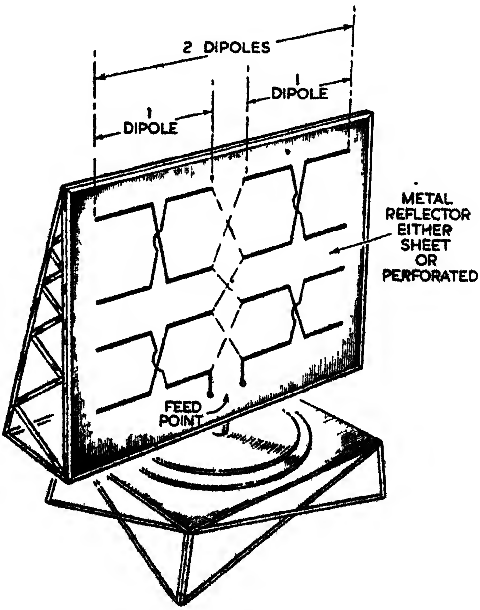


FIG. 14.—A COMMON TYPE OF AERIAL FOR USE WITH LONG-RANGE WARNING SETS.

The aerial is formed from 8 sets of dipoles, stacked 2 dipoles wide and 4 dipoles high. The dipoles are fed in phase, in pairs.

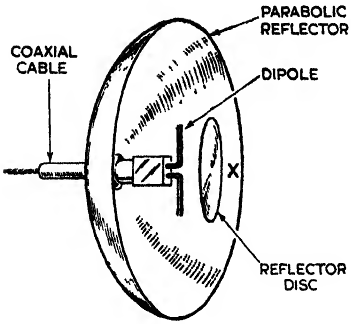


FIG. 15A —DIPOLE WITH PARABOLIC REFLECTOR

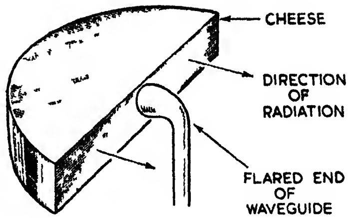


FIG. 15B.—" CHEESE " FOR RADIATING AND COLLECTING ELECTROMAGNETIC ENERGY.

Radar aerial systems for use with long range warning sets usually consist of a group of stacked dipoles, with either a sheet of metal for reflector or, in cases where wind resistance must be reduced to the minimum, a perforated reflector (see Fig. 14), or just simple rods. Aerials for use in the centimetre range, fed by waveguides or concentric cables, may take the form of those shown in Fig. 15. For example, Fig. 15 (*a*) shows a dipole fed by a coaxial cable. The disc " X " reflects nearly all the R.F. energy radiated by the dipole to flood the surfaces of the parabolic reflector and the parabolic reflector radiates this R.F. energy as a narrow beam. The beam width is determined by the dimensional relationship between dipole and reflector and the geometry and disposition of both of them.

In (*b*), energy from the flared end of the waveguide is flooded over the parabolic mirror " cheese " and radiated outwards into space from the " cheese " as a narrow beam. These are only examples of the many types of Radar aerial which are in use.

BASIC PRINCIPLES OF RADAR SYSTEMS

The basic set-up for a Radar system is shown in Fig. 16, in block diagram form. This consists of a transmitter or R.F. generator, a sensitive receiver with video output, an indicator which includes a cathode ray tube and its associated time base and amplifier circuits, an aerial system including radiator, feeder system and transmitting-receiving switch. Finally, the system

must incorporate some means for co-ordinating, or synchronizing the following operations :—

(*a*) The commencement of each pulse of R.F. energy.

(*b*) The commencement of each sweep of the time base voltage, i.e. the commencement of each trace.

(*c*) The brightening up of the trace for the period of each sweep, i.e. increasing the intensity of the electron beam for each sweep duration.

The flyback is timed by the fall of the time base voltage to zero and the dimming of the electron beam takes place at the end of each completed sweep of the time base voltage because the duration of each brightening pulse is made equal to the duration of the sweep or to the time for the completion of each trace. The synchronizing function for *a*, *b* and *c* may be performed by pulses from (1) a master synchronizing circuit, (2) by a pulse from the transmitter to the indicator, (3) sometimes by a pulse

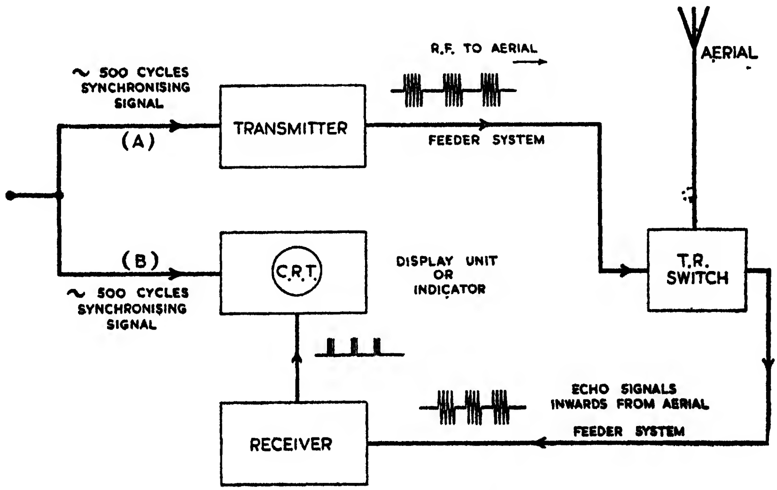


FIG. 16.—BASIC RADAR SYSTEM.

A and B are sychronizing signals supplied from, say, the A.C. mains at 500 cycles per sec, to the Transmitter Unit and Display Unit, respectively.

A and B establish the repetition rate for the System at 500 cycles per sec., and start the Time Base Generator in the Indicator at the same instant that each transmitted pulse of R.F. commences.

B also times the application of a positive pulse to the control grid of the C.R. Tube in order to intensify the electron beam from the instant that the Time Base generator starts up, until it completes one sweep.

All these operations are repeated 500 times per second.

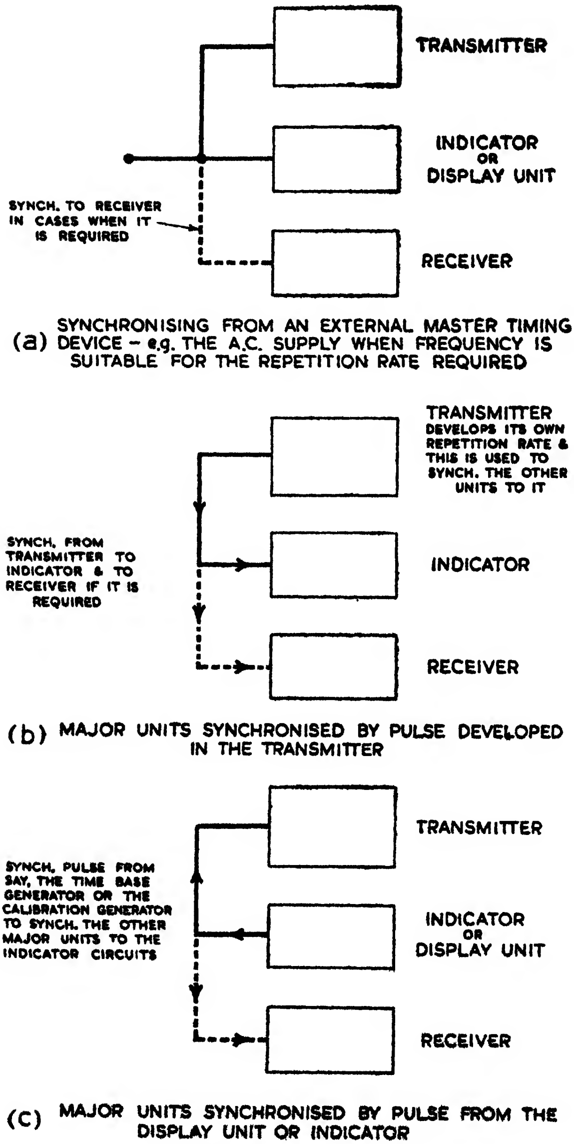


FIG. 17.—BASIC SYNCHRONIZING SYSTEMS.

from the indicator to the transmitter. These three methods are shown in Fig. 17. The methods enumerated above are not the only alternatives, but they serve to indicate the principle employed for synchronizing the operations of the units concerned. More complex set-ups employ the same basic principle, but of course, as more refinements are employed, additional pulses must be supplied from the synchronizing or timing source, in order to perform the additional co-ordinating functions.

No matter how many synchronizing pulses are required, they must all be controlled from the same source. In the basic set-up just described an independent master synchronizer, the transmitter, or some circuit in the indicator unit assumes the responsibility for timing the various operations throughout the system.

In some cases it is necessary to render the receiver inoperative during the period of transmission. This can be done by means of a pulse which increases the bias of some of the valves in the first I.F. stage for the duration of the transmitting pulse; alternatively, the H.T. can be removed entirely from one or more valves in the receiver during transmission. This necessity arises when it is desired to receive echoes from targets very close to the transmitter, the reason being that the time between the end of each transmitted pulse and the instant of arrival of the echo is so short that the receiver must be in a state to receive efficiently immediately the transmitted pulse has ceased. If the transmitter employs high power it tends to paralyze the receiver for a short time after transmission ceases, due to static charges accumulated in bias circuits and the like. In these circumstances, it is usual to render the receiver inoperative, or partially so, during each transmission period, thereby reducing the *recovery time* and enabling signals from nearby targets to be received. *Recovery time* determines *minimum range*.

Fig. 18 shows the time relationships for operation of the major functions in the basic Radar system.

Calibration and Range Mark Generators

Expansion of the Basic Radar system by the addition of refinements is exemplified by the provision for calibration, which is made in nearly every case.

The method of subdividing the cathode ray tube trace by means of a superimposed transparent scale is obviously not in itself very

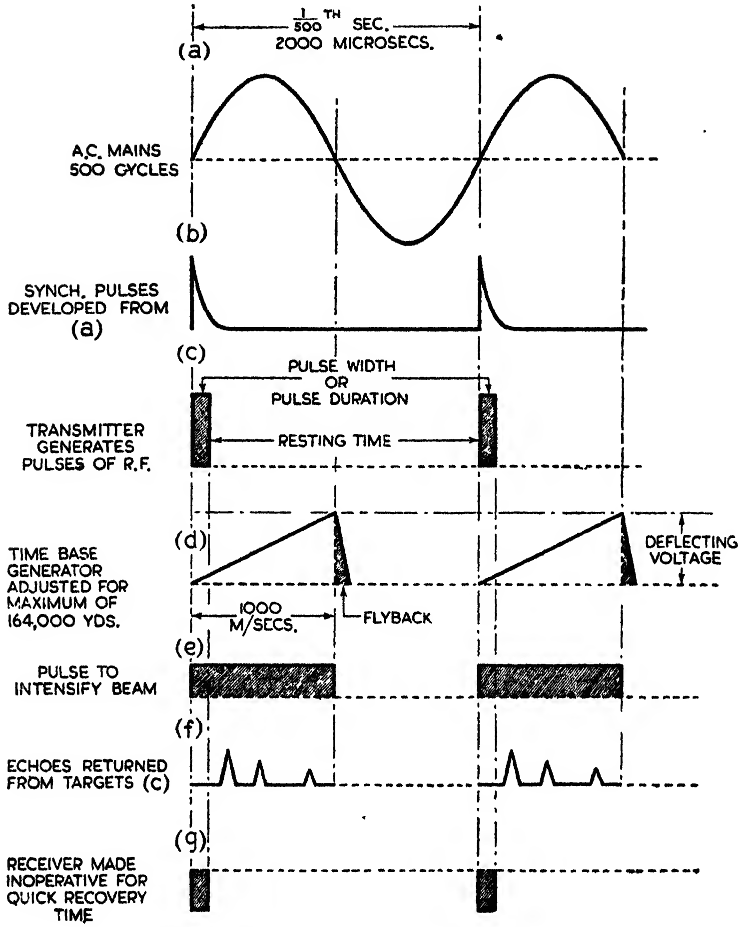


FIG. 18.—TIME RELATIONSHIPS IN BASIC RADAR SYSTEM.

Major units synchronized by external Master Timer. In this instance, the A.C. supply at 500 cycles per second.

accurate. Variations in the Time Base circuits, due to ageing or change of values of components, must cause inequalities and change of speed in the rate of deflection of the beam across the screen, and therefore in the trace which it produces. Some means must clearly be provided for detecting and correcting such changes. Accordingly, a calibrator circuit is provided for this purpose. In the simplest form of calibrator a generator

is caused to start up at the same time as the time base generator by a synchronizing pulse. This generator produces signals at equal intervals of time, which are in effect equal time subdivisions of the main Time Base trace. The signals generated by the calibrator circuits are mixed with the receiver output on the "Y" plates of the "A" display and appear along the trace as bright marks at *equal time intervals.* If the time base circuits have altered, these will not line up with the fixed subdivisions of the transparency. In this case provision is made whereby the speed of the time base circuit can be adjusted in order to bring the calibration marks into alignment with those of the fixed scale. This operation must be performed periodically, and a pulse additional to those shown in Fig. 18 is required from the synchronizing source for the calibration generator, which is not shown in that Figure.

In many cases, where the A.C. supply is at 500 cycles, this is used as the synchronizing source from which the synchronizing pulses are sent out to the various units which are to be co-ordinated. In other cases, where the frequency of the supply is too low, a master circuit develops a synchronizing signal at the required frequency. This may be done by a Wien Bridge Oscillator, for example. Some forms of transmitter, however, develop their own repetition frequency, and in this case a pulse may be taken from the transmitter to synchronize the other units and the necessity for an external master timing device or synchronizer does not arise. Also cases arise where it is necessary to synchronize all the units by means of a pulse from either the sweep generator or from the Range Mark generator in the indicator unit (see Fig. 17). If is, of course, impossible to enter into a description of all these variations here.

Major Units and Constants

The form of transmitter selected for a Radar system depends almost entirely upon the frequency which has been selected, and this in turn, as we have already seen, depends upon the application. Standard triodes, due to their inter-electrode capacity, are unsuited to operate in circuits generating frequencies of more than about 200 megacycles. Special triodes are available for frequencies up to about 400 megacycles, but for all frequencies above about 400 megacycles the magnetron is almost universally employed in R.F. generators.

The constants of the Radar system are pulse width or pulse duration, repetition frequency or repetition rate, average power, peak power and duty cycle.

Pulse Width or Pulse Duration.—The pulse width or pulse duration is the length of time in each transmission for which R.F. energy is radiated. This is only another way of saying that it is the length of time for which the R.F. generator is operating. The *minimum range* at which a target can be received is determined largely by the pulse width. If the target is so close to the receiver that the echo is returned to it before the transmitter is turned off, the echo will be masked. The maximum limit of pulse width for a particular system is therefore determined by the nearness of the target which the Radar set is required to detect. In the case of long range warning sets, the pulse width may be longer than for short range, precision sets, especially if the latter are to be designed to pick up buoys and similar navigational marks at close range for navigational purposes.

Pulse Repetition Frequency or Rate.—Sufficient time must be allowed between transmitted pulses for an echo to return from the most distant target at extreme range. If this is not done, returning echoes will be obscured by succeeding transmitted pulses. This necessary time interval fixes the highest frequency that can be used for the pulse repetition rate. It means that the lower limit of the permissible repetition rate for a long range warning set is below that of the lowest permissible rate for a short range precision set. When the aerial is rotated at constant speed, as is the case in some applications, the beam of energy strikes a target for a very short time, therefore a sufficient number of pulses must be transmitted in order to ensure a reasonable echo. The persistence of the screen of the cathode ray tube and the rotating speed of the aerial also effect the minimum desirable repetition rate.

Average Power.—The power output rating of a valve as given by the manufacturer, is determined by its power handling capacity over a continuous period of time. This is known as *Average Power.*

Peak Power.—In Radar, transmission takes place in short pulses with comparatively long resting periods in which there is time for the valve to cool. When operated in this manner, a valve can handle a peak power, for very short periods, of many

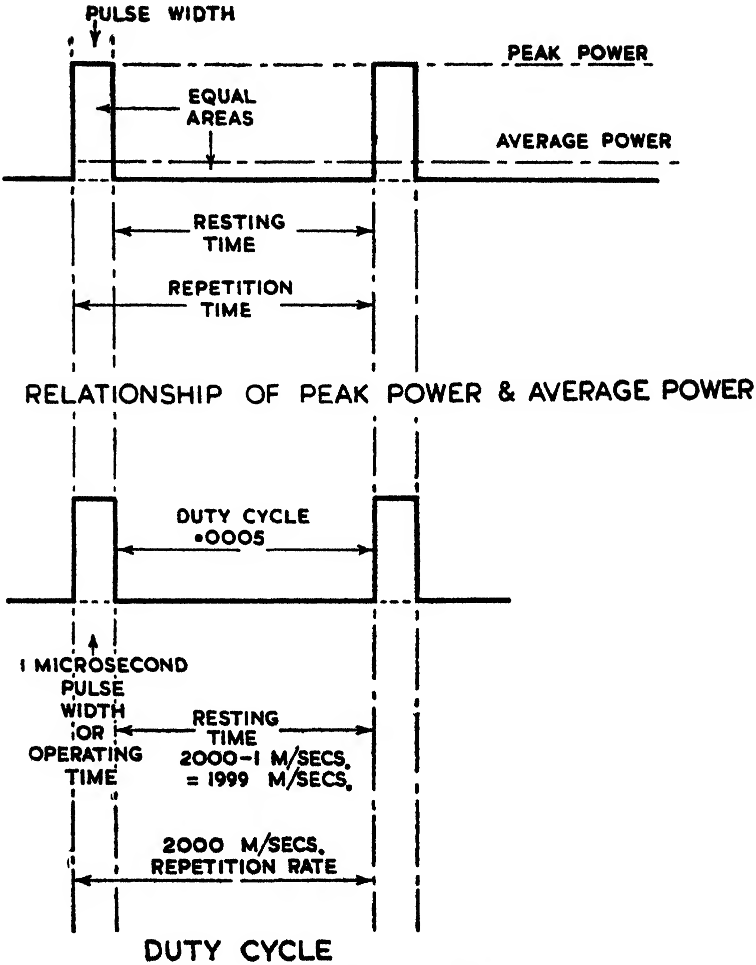


FIG. 19.—RELATIONSHIP OF PEAK POWER, AVERAGE POWER AND DUTY CYCLE.

times the value of its average handling power capacity for continuous working. The useful power of a Radar transmitter is contained in the radiated pulses, and is therefore termed the *Peak Power* of the system. Since the Radar transmitter is resting for a long time compared with its operating time, the average power delivered during one cycle of operation is quite low compared with the peak power available during pulse time.

A definite relationship exists between the average power dissipated over an extended period of time, and the peak power developed during pulse time. The time for 1 cycle of operation is 1/ frequency, thus the greater the pulse width the higher the *average power*, and the longer the pulse repetition time the lower the *average power*.

Therefore :—

$$\frac{\text{Average power}}{\text{Peak power}} = \frac{\text{pulse width}}{\text{pulse repetition } \textit{time}.}$$

The operation of the Radar transmitter can be described in terms of the fraction of the total time that the R.F. energy is radiated. This time relationship is called the duty cycle :—

$$\text{Duty Cycle} = \frac{\text{Pulse width}}{\text{Pulse repetition time.}}$$

The general relationships are shown in Fig. 19.

The following examples should make the matter clear :—

A two microsecond pulse repeated at 800 times per second represents a Duty Cycle of—

$$\frac{\frac{2}{10^6}}{\frac{1}{800}} = 0{\cdot}0016$$

Since Pulse width/Pulse repetition time = Average power/Peak power, then—

$$\frac{\text{Average power}}{\text{Peak Power}} = \text{Duty Cycle.}$$

Suppose that a 1 microsecond pulse is repeated 500 times per second and that the average power is known to be, say, 100 watts the peak power can be obtained as follows :—

$$\text{The Duty Cycle is } \frac{\frac{1}{10^6}}{\frac{1}{500}} = \frac{1}{10^6} \times 500 = \frac{1}{2{,}000} = 0{\cdot}005$$

$$\text{Peak Power} = \frac{\text{Average Power}}{\text{Duty Cycle}} = \frac{100}{0{\cdot}0005} = 200 \text{ kw.}$$

This means that a valve normally rated at 100 watts for continuous working can produce a pulse with a power peak of 200 kilowatts for 1 microsecond, 500 times per second.

From the foregoing considerations it is clearly desirable to keep the duty cycle small in order that the peak power may be as large as possible. The general tendency, therefore, is to fix the repetition frequency somewhere in the region of 500, and pulse widths vary from somewhere in the region of 5 microseconds for long-range warning sets to 1 microsecond and less for short-range precision sets.

Large peak outputs are generally obtained by considerably increasing the H.T. voltage applied to the transmitting valves. The H.T. for a particular valve is limited by the geometry and spacing of the valve electrodes, since this determines the voltage at which arc over can take over. Power is proportional to E^2.

Transmitters

Transmitters for Radar may be classified under two main headings, viz., transmitters for frequencies up to about 400 megacycles, and transmitters for frequencies above this value. This first classification arises from the fact that triodes and special triodes may be used in R.F. generating circuits, efficiently, up to about 400 megacycles ; for frequencies above this value, as we have already mentioned, the magnetron is almost universally employed.

The limiting frequency for triodes and special triodes is brought about by :—

(*a*) Inter-electrode capacity of the valve.

(*b*) Inductance of the electrode leads.

(*c*) Transit time of the electron.

(*d*) Physical shrinking of external capacities and inductances to impracticably small sizes.

(*e*) Consequent approach to the frequency limit of the valve itself, i.e. the oscillation frequency that will occur due to its internal capacities and inductances when the electrodes are externally connected in circuit by the shortest possible conductors.

(*f*) Losses due to : skin effect, large capacity charging currents, eddy current losses in adjacent conductors, dielectric loss in the glass envelope, seals and pinches, energy loss by direct radiation from the circuit.

Special triodes have been employed for frequencies up to 600 megacycles, but generally in very small transmitters, at considerably reduced efficiency.

Classification of Transmitters.

Sub-classifications of transmitters relate to the method of pulsing: (1) Transmitters included in the first classification, up to about 400 megacycles, may be either self-pulsed, or pulsed by the application of a high voltage power pulse developed externally; (2) Transmitters for frequencies above say, 400 megacycles, and using a magnetron, are always externally pulsed by the application of a very high voltage high power pulse developed externally from the magnetron itself. The magnetron and its associated input and output circuits convert this high voltage high power pulse into a pulse of R.F. at the required carrier frequency.

Classification of Pulsing Systems

The important difference in the two forms of pulsing is that when a self-pulsed transmitter is used it develops its own repetition frequency, and the repetition frequency so developed is used to synchronize the other units of the system. The frequency of self-pulsing R.F. generators is not, however, very stable, and therefore the repetition frequency is not sufficiently constant for use with sets required for accurate measurements. It has the advantage, however, of being economical as regards space and weight and is relatively simple to operate. Self-pulsed R.F. generators are therefore used when some instability of the repetition frequency can be tolerated and when lightness, simplicity and compactness are important.

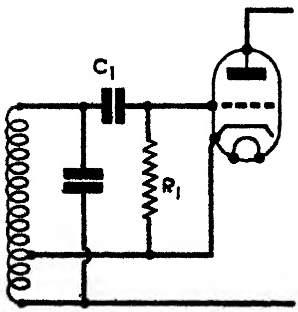


FIG. 20.—HARTLEY TYPE OSCILLATOR.

This circuit can be arranged as a self-pulsing oscillator by adjusting the values of C_1 and R_1.

The circuit of a self-pulsing oscillator is shown in Fig. 20. The principle is briefly described in a later paragraph.

High voltage, high power pulses for application to R.F. generators can be developed either at low level or at high level. High voltage, high power pulses, developed at low level, can be

produced at any desired repetition rate and the degree of rate stability can be established within very narrow limits of variation. This method, however, employs a large number of circuits, occupies considerable space and adds to the weight of the equipment as a whole. It can be used for very precise measurement, and in cases where a suitable A.C. frequency supply or other means of synchronizing is not available. The block diagram in Fig. 21 is an example of the method employed in producing high voltage high power pulses from a synchronizing signal at low voltage level.

Fig. 22 shows the method of producing high voltage high power pulses at high level. In this method the frequency of the discharge of high voltage across the spark gap determines the repetition frequency, and the other units of the Radar system are usually synchronized by a pulse from the transmitter when the high-level method is employed. This method has several advantages. In the first place, it can deal with pulses of very high power, since a spark gap can be designed to operate at any reasonable voltage. Voltages employed in this system to produce the necessary power may be of the order of 30,000 volts or more, and the peak power developed may be of the order of a megawatt.

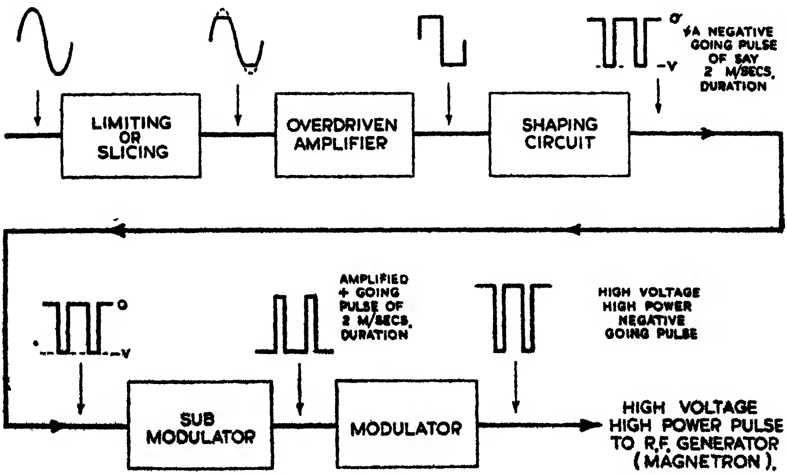


FIG. 21.—DEVELOPMENT OF HIGH VOLTAGE, HIGH POWER PULSES AT LOW LEVEL.

An example of the method used to produce pulses of this nature from a synchronizing signal at low voltage level.

The combination of artificial line, together with a rotary discharger is simple and highly efficient. It suffers from two disadvantages, however, viz.: Some slight instability of the repetition frequency due to the vagaries of the discharge. This is inherent in all spark gaps, because ionization as a prelude to discharge is itself somewhat irregular. Secondly, the waveform of the pulse from the artificial line depends entirely upon the goodness of the artificial line. In this system there is no possible opportunity to correct any defects in the waveform of the high voltage high-power pulse output before it is applied to the magnetron.

From what has already been said regarding the classification of transmitters and the high voltage high power pulses by which they are fed it is clear that examination of any Radar system discloses that its composition must be analyzed under two separate headings :—

1. The major units comprising the system.
2. The pulsing system by which they are operated and synchronized.

Three classes of pulses can be readily distinguished :—

(*a*) Trigger pulses proper.

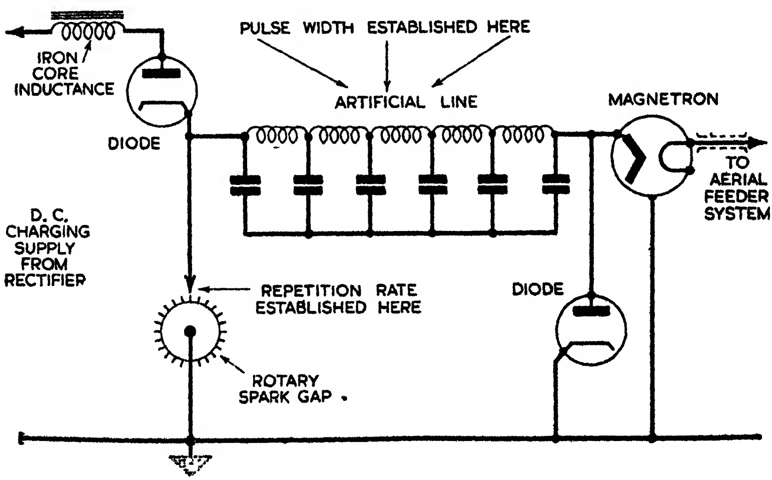


FIG. 22.—DEVELOPMENT OF HIGH VOLTAGE, HIGH POWER PULSES AT HIGH LEVEL.

The peak power developed in this system may be in the region of a megawatt.

(*b*) High voltage, high power pulses to operate the R.F. generator for definite periods of time.

(*c*) Low voltage, low power pulses, also having a definite time duration for various purposes.

Development of Pulses

Trigger pulse waveforms are generally sharp-pointed with steep leading edges ; rising almost vertically to some given peak voltage. These pulses are generally used when it is desired to drive a valve into conduction or when it is desired to drive it momentarily into the cut-off state. Synchronizing pulses, when they do not combine a timing function, generally fall within the trigger pulse classification.

Trigger pulses may be developed from a sine wave by a sequence of shaping and dimensioning operations. These might be, for example, a limiting or slicing operation which roughly squares the sine wave, this roughly squared output may then be improved by an operation performed on it by an overdriven amplifier. The output from this stage is generally a good rectangular wave, with steep sides and a duration of approximately half the time period for one cycle of the A.C. input. The next operation is to develop a voltage wave, the peak value of which is proportional to the rate of change of the input voltage across the resistance in an RC circuit (differentiation). In this way a voltage wave with a sharp-pointed peak and steep leading edge may be developed at a repetition frequency equal to that of the input sine wave. Such pulses are very suitable for synchronizing, with or without amplification, according to requirements.

High voltage, high power pulses, with a fixed time duration suitable for pulsing R.F. generators have already been dealt with, see Fig. 22.

Low voltage, low power pulses may be developed in a variety of ways and are suitable for synchronizing and timing the duration of operation of time base generators, range mark generators, strobe generators, brightening pulse generators and various similar functions in the indicator and the receiver circuits.

These low voltage, low power, time control pulses may be developed from a sine wave input by squaring operations similar to those employed in the initial stages of development of the trigger pulse, but instead of a differentiating operation following upon this, the output square wave obtained from the sine wave

must be adjusted for time duration. This means that the width of the flat top must be made proportional to any time duration that may be required. This operation can be performed by an amplifier having an input circuit somewhat similar to that which is used for the production of trigger pulses, but the amplifier is biased in a different manner. On the other hand, alternative circuits are available for producing low voltage, low power pulses such, for example, as one of the many forms of multivibrator circuits, the phantastron, the artificial line, etc.

In general, the pulsing system for any assembly of major units may be laid out in several ways, by using different combinations of pulses and pulse-generating circuits.

The object of the Radar engineer is, of course, to lay out the pulsing system in the most efficient and economic manner, hence Radar systems differ widely, not only in respect of the types employed for the major units, but also in respect of the entire pulse system layout which is designed to be suitable for the requirements of the type of major units employed, and at the same time as efficient and economical as possible.

Beyond the very general statement that circuits and devices for shaping and dimensioning (electrically), the large variety of pulses used in Radar depend largely upon the deliberate introduction of distortion into amplifier circuits, it is not possible, in the space available, to attempt any detailed description of how these functions are performed. It can, however, be said that a knowledge of the factors which produce distortion in amplifier circuits and the manner in which they operate is essential.

We should now return to a consideration of the major units, viz.: the transmitter, the aerial system, the receiver and the display unit.

TRANSMITTERS

The Self-pulsing Oscillator

In the circuit shown in Fig. 20 the R.F. frequency is determined by the L.C. constants of the circuit. Bias for the valve is provided by grid current which charges C1 through the cathode-grid resistance R1. R1 permits C1 to discharge during the portion of the cycle in which the grid is not positive to the cathode. The result is that the bias on the grid is proportionate

to the voltage across the grid input circuit and stable oscillation conditions exist.

If the time constant of C1, R1 is increased by increasing either C or R the charge on C1 cannot leak off fast enough to follow the fluctuations of voltage caused by irregularities of the electron stream. As a result the charge on C1 grows with each successive cycle, until a point is reached where the voltage across C1 is too high to permit feedback of the amount of energy required from the anode circuit to maintain oscillations. Oscillations therefore cease, and cannot start again until the voltage across the condenser C1 has fallen, by leakage, to a value sufficiently small to pass from the anode circuit the necessary amount of feedback required to start up the oscillatory action of the valve again.

Push-Pull R.F. Generator Circuit

The R.F. generator shown in Fig. 23 is a tuned grid, tuned anode push-pull self-pulsing oscillator, using pairs of quarter-wave sections of transmission line to act as parallel resonant circuits in place of the usual coils and condensers.

The use of quarter-wave transmission lines provides a high "Q" for the oscillatory circuits, and the R.F. frequency stability of the generator is therefore good. Oscillators of this type are usually designed to have as much inductance as possible and to oscillate with the valve internal capacities, the latter providing the channel for the necessary feedback for the maintenance of oscillations. In a push-pull type of oscillator, the inter-electrode capacities are in series and, therefore, their effective capacity is reduced to a minimum. The charging currents are also half the value of that for a single valve.

The transmission lines forming the external resonant circuit are extensions of the internal leads to the valve electrodes. By this arrangement the inductance of the internal leads is used as part of the oscillatory circuits. The "Q" of the circuit is large because the inductance and capacity of the external resonant circuit are distributed, and because the skin effect can be reduced by using conductors of large diameter (with consequent large circumferential conducting area). Resistance can be further reduced by silver plating the tubes forming the resonant lines.

The length of the quarter-wave line in the grid circuit is physically less than the quarter-wave line in the anode circuit,

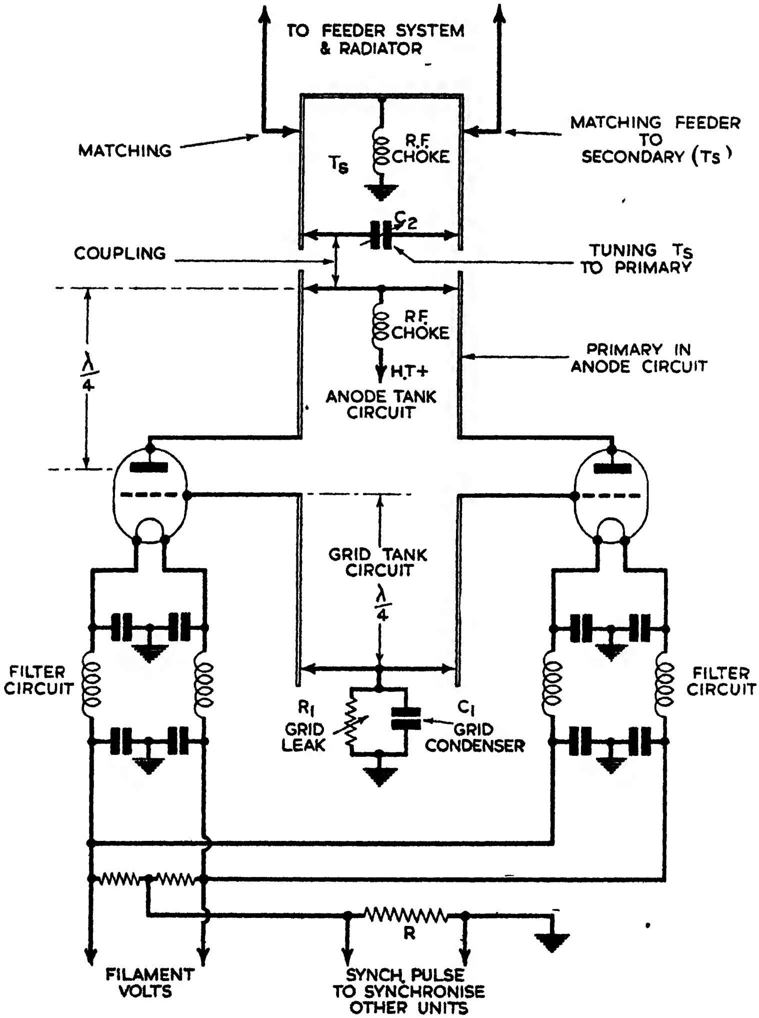


Fig. 23.—Push-Pull R.F. Generator Circuit for V.H.F. Pulsed Transmission.
Tuned grid, tuned anode, push-pull, self-pulsing R.F. generator for use at about 100 to 200 megacycles.

because the internal capacity from grid to cathode is greater than the internal capacity from anode to cathode.

Theoretically the shorting bar has zero potential at its electrical centre. It is therefore convenient to connect the H.T. + to this point. Energy in the anode circuit is coupled to the feeder by

the circuit marked TS. This acts effectively as the secondary of a transformer. The two-wire transmission line to the feeder is connected to the coupling line at the point at which the impedance of the coupling line is equal to the impedance of the transmission line.

The synchronizing pulse for the indicator circuits—to synchronize the start of the time base generator and the brightening of the trace to the start of the transmitter—is taken across R. The bypass and filter circuits in the filament leads are mainly for the purpose of reducing the effects of negative feedback and the loss of output power that would result from this undesired effect.

Pulse Control

C1 and R1, the values of which control the pulsing action, are shown in Fig. 23 and marked accordingly. The duration of the pulse is determined by the capacity of C1, *i.e.*, by the time required to charge it. This time is affected by any factor that affects the magnitude of the grid voltage such, for example, as the tuning of the primary to the secondary, the value of the H.T. voltage, the tuning of C2 to the coupling line, the position of the transmission line taps and the degree of coupling.

When the transmitter is tuned for maximum power output, therefore, the pulse duration is controlled by the capacity of C1. The pulse repetition rate can be varied by most of the adjustments that effect the pulse duration. Changing any one of these values causes C1 to be charged to a slightly different voltage, and it therefore takes a different time for C1 to discharge to the voltage at which the valve can again begin to oscillate. The practical method of altering the repetition rate is to change the value of R1, which is usually made variable, in steps, for this purpose.

Magnetron R.F. Generators

Fig. 24 shows the input and output circuits for a magnetron R.F. generator. Fig. 24a is without pulse transformer. Fig. 24b is with pulse transformer. The functions of the pulse transformer are (1) to match the output conditions of the pulse forming circuit to the input of the magnetron, (2) to permit the magnetron and waveguide assembly to be located remote from the main operating position, *i.e.*, close to the

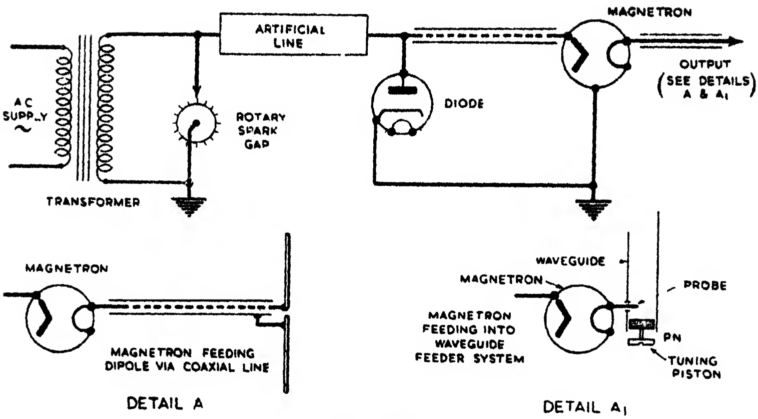


FIG. 24*a*.

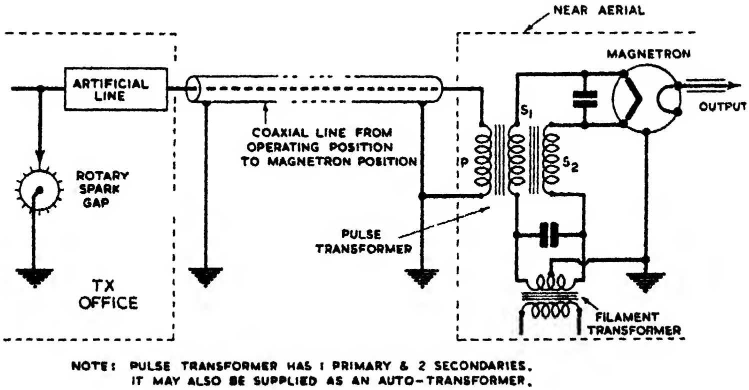


FIG. 24*b*.

FIG. 24—INPUT AND OUTPUT CIRCUITS FOR MAGNETRON R.F. GENERATOR.
(*a*) Without pulse transformer.
(*b*) With pulse transformer.

aerial, and (3) to enable a lower voltage to be generated in the primary circuit, since it can be stepped up to the required value before application to the magnetron.

The output from the magnetron is via the small looped probe which feeds directly into the waveguide feeder system. Matching is performed by the piston marked PN in the sketch.

The magnetron used in modern Radar transmitters is of the resonant type and is a development of the split anode magnetron, the action of which is briefly described later in this chapter.

Feeder Systems

Frequency is the factor which determines whether co-axial cable or waveguides are to be used to feed energy from the magnetron output to the radiator. The "Q" of a waveguide is very much higher than that of a co-axial line, and is therefore to be preferred for minimum attenuation, but an essential requirement of a waveguide is that one of its dimensions must be not less, generally rather more, than half a wavelength at the frequency at which it is to be used. This means that although waveguides are very desirable on account of their high efficiency, their use is restricted to those frequencies at which the essential minimum dimension becomes small enough to be a practicable proposition.

Waveguides

The advantages of waveguides may be enumerated as follows: (1) Complete shielding and therefore no radiation loss; (2) No dielectric loss; (3) Copper loss less than that of a co-axial line of the same size operated at the same frequency; (4) Greater power handling capacity than for a co-axial line of the same size. This arises because power is proportional to E^2 since a waveguide has no centre conductor, the distance between opposite potential surfaces for equal external dimensions is twice that of a co-axial line. This means that the waveguide can handle larger voltages without arcing over and therefore more power. (5) Finally, construction with a waveguide feeder is simpler than with a co-axial line.

When considering the action of waveguides it is very useful to remember that, whilst it is a convention to explore the distribution of electrical energy in a circuit by means of the voltage and current, we might also explore it by considering the electric and magnetic fields associated with these voltages and currents. When we come to the waveguide, which is a simple hollow tube, the measurement of voltages and currents are impracticable, therefore we adopt the obvious alternative of considering the electric and magnetic fields that are set up inside the guide by the electrical energy which is introduced into it.

Electrical energy may be introduced into a waveguide as an electric field at R.F. frequency or as a magnetic field at similar frequency. The state in which the energy is introduced is determined by the probe and its location in the guide. The

mode of oscillation along the length of the guide is determined by the manner of introduction of the electrical energy into the guide and the geometry of the guide itself, *i.e.*, the relative positions of reflecting surfaces, etc.

Waveguide Feeder Systems

A waveguide may be thought of as a long rectangular box of ether, open at one end and closed at the other, as shown in Fig. 25. The dimensions of this box should be such that one side is at least half a wavelength long at the frequency at which the guide is to be used, the shorter dimension should be such that the distance between the two longer sides provides sufficient air insulation to prevent arc-over at the voltage at which the guide is to be operated.

The guide is generally made of thin sheet metal with a smooth internal finish which may be silver-plated to reduce skin effect. In some cases air conditioning plant is installed in connection with the waveguide system in order to maintain the air in the guide dry and free from moisture. The probe which introduces the R.F. energy into the guide is straight when it is desired to introduce or collect from the electric field component of the R.F. energy, and looped when the probe is concerned with the magnetic component. There are alternate positions in the top ends or sides of the waveguide where the probe may be inserted, and the position thus selected determines the manner of oscillation of the energy and hence the patterns of the electric and magnetic fields which are excited.

In other words the position of the probe in the guide with regard to the various internal reflecting surfaces determines the pattern of the electric or magnetic field that will be excited. These patterns of excitation are called " modes."

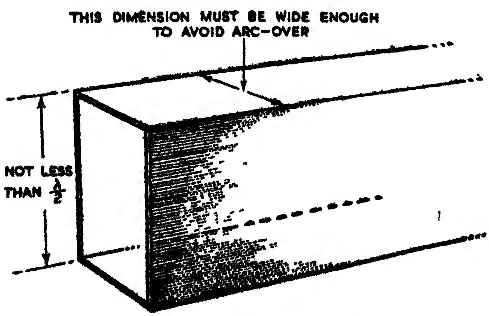


Fig. 25.—Minimum Dimensions of Waveguide.

Waveguides may be either rectangular, as described above, or circular. The rectangular type of guide is usually employed for the main feeder, with a

section of circular guide inserted when it is desired to make a rotating joint.

The method of introduction of the R.F. energy into a waveguide determines the plane of polarization at the output, and the sections of circular guides are used at rotating joints in order to ensure that the polarization at the output shall be in the desired plane.

How a Waveguide Functions

The machinery of propagation of R.F. energy along a guide is somewhat involved and cannot be fully described in a space so brief. It can only be said that the R.F. energy introduced into the box of ether, which we call a waveguide, initially as an R.F. alternating electric field, or as an R.F. alternating magnetic field, is reflected. If both ends of the waveguide are closed, standing waves of electric and magnetic energy appear along the length of the guide in a manner very similar to the phenomena observed in connection with transmission lines. If the distant end of the guide is open, and suitably flared, so that the impedance of the guide is matched to free space, the R.F. energy sees an unchanged condition, electrically, stretching away into infinity, and moves down the guide to the radiator, where it is radiated into free space as a beam of more or less narrow dimensions, according to the geometry of the radiating and reflecting system.

Progress along the guide may be thought of, as produced by a series of progressive reflections from wall to wall along the length of the guide. *The ether energy associated with this series of progressive electrical reflections moves down the guide with a velocity of* 186,000 *miles per second.*

Co-axial Cables

When a co-axial cable is used, the R.F. energy is fed to a suitable dipole. The energy radiated by the dipole is nearly all re-distributed, to flood the main radiator, by means of a reflector placed in front of the dipole. The waves are vertically, or horizontally, polarized according to the plane in which the dipole is erected.

Transmitting Receiving Switch

In order to prevent loss of transmitted energy in the receiver, and the possibility of causing damage to it as well as to avoid loss of energy in the transmitter when receiving, an electronic switch

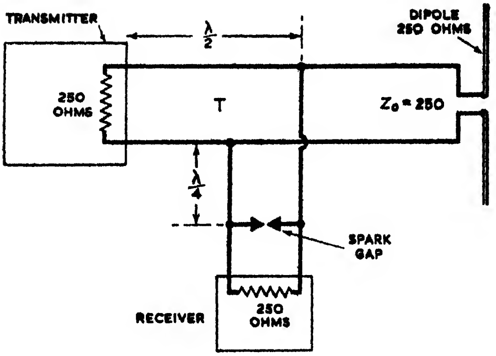


FIG. 26. ELEMENTARY ARRANGEMENT FOR T.R. SWITCHING.

The pulse from the transmitter divides at the T-joint; part goes to the receiver branch and causes the spark gap to break down, the rest goes to the aerial.

is employed in the aerial feeder system. This is usually called the T.R. switch. The simplest method of overcoming the difficulty would be to use separate aerials for transmitting and receiving, but this is uneconomical and bulky.

This problem of switching is simplified to a certain extent by the fact that the impedance of the transmitter during operation is different to that during resting periods. Fig. 26 shows an elementary arrangement for T.R. switching. " T " is a junction point in the feed line, where the receiver feeder joins the transmitter feeder, both being connected to the radiator via the third feeder. For purposes of illustration it is assumed that the characteristic impedance of the transmission line, the feed point resistance of the aerial, the input impedance of the receiver and the output impedance of the transmitter when generating R.F.

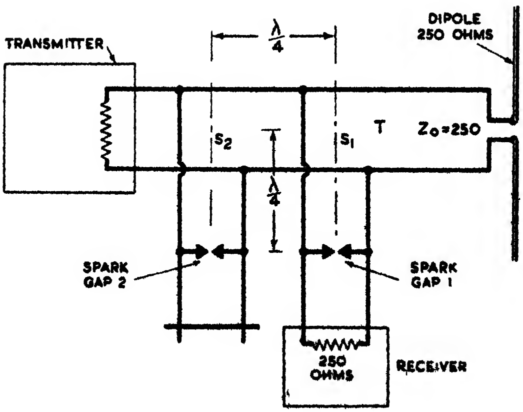


FIG. 27. ANOTHER FORM OF T.R. SWITCHING.

A second spark gap is employed when the simple T.R. switch affords insufficient protection.

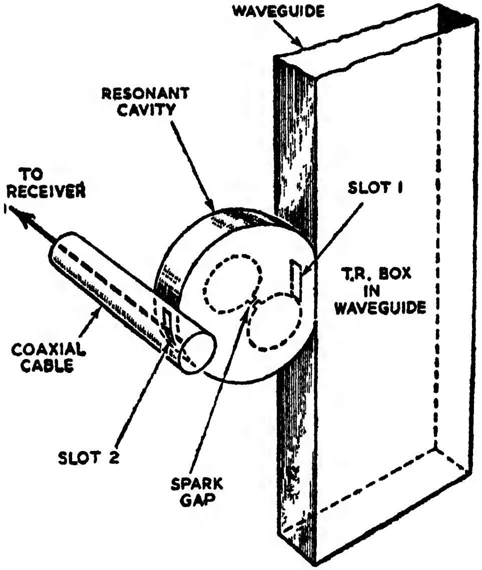


FIG. 28.—T.R. SWITCHING FOR WAVEGUIDE SYSTEMS.

A resonant cavity and spark gap are employed. The T.R. box is coupled to the waveguide by slot 1 and coupled to the receiver via slot 2 and the coaxial line.

power are all 250 ohms. The transmitter output impedance rising between pulses to 5,000 ohms and the resistance of the conducting gap (conducting) is 50 ohms.

The pulse from the transmitter divides at the T-joint, part goes to the receiver branch and causes the spark gap to break down and the rest goes to the aerial. The breakdown of the spark gap places a resistance of 50 ohms across the 250-ohm line just a quarter wavelength from the " T " junction. By transmission line theory, the " T " junction end of the quarter wave line, now terminated in 50 ohms at the receiver end, will exhibit an impedance of 1,250 volts at the " T " junction, and the transmitter pulse has the choice of a 1,250 ohm path to the spark gap, or a 250 ohm path to the aerial. Since the aerial terminates the transmission line in its characteristic impedance, most of the energy passes to the aerial whilst the remainder is used to keep the spark gap going.

At the end of the pulse, the gap is de-ionized and receiving signals reach the " T " junction. Again there is a choice of two paths. The receiver path has an impedance of 250 ohms (since the spark gap is now open circuited). The path to the transmitter is, however, made a half wavelength, and since this is

terminated in 5,000 ohms, received signals coming towards the "T" junction meet an impedance of 5,000 ohms. Most of the received signal now goes to the receiver and very little goes to the transmitter.

When the output resistance of the transmitter does not change sufficiently to permit the use of a resonant line alone in blocking receiver signals from the transmitter, a second spark gap is used as in Fig. 27. This is merely the system shown in Fig. 26, plus the addition of a further switch. The transmitted pulse passes down the line to spark gap 2 and causes it to arc over, the resulting short circuit is reflected back to the main feeder as a high impedance by the action of the quarter wave line. During the transmitted pulse, switch 2 merely uses a small amount of power in its spark gap and switch 1 functions as before. Switch 2 is in effect an open circuit during the resting period because the shorting bar which is a quarter wave below the gap is reflected by the half wave line of switch 2, as a short circuit across the transmitter feed line. This is reflected in turn to the "T" junction as a high impedance by the quarter wave section of the feed line between the two joints, thus blocking the transmitter channel for all received signals.

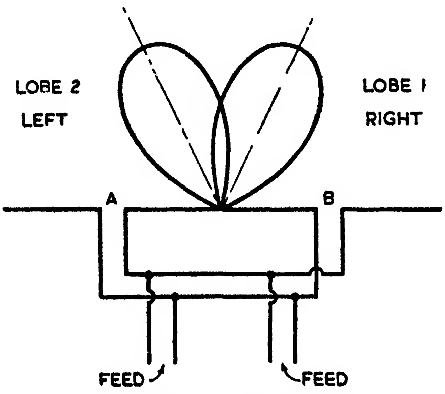


FIG 29.—AERIAL ARRANGEMENT FOR BEAM SWITCHING

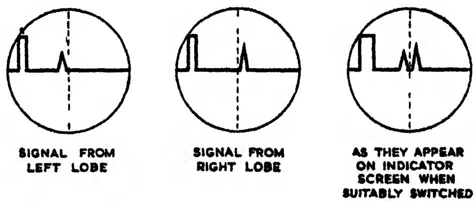
A similar system is used to perform the T.R. function when waveguides are used. Instead of the resonant lines, however, resonant cavities are employed with internal spark gaps across the high potential sides of the cavity. The resonant cavities take the place of resonant quarter wave sections of transmission line. Break down of the spark gap destroys the resonant properties of the cavity resonator during the time the gap sparks over. Consequently resonant cavities and spark gaps can perform the same functions, when employed in wave-guide feeder systems as do quarter wave sections of transmission lines with spark gaps fitted in a transmission line feeder system.

Beam Switching

In Fig. 29, an aerial, four dipoles wide, is used to receive echoes from targets and to measure their bearing. The aerial is divided into a left half A, and a right half B, connected by an external feed line, a section of which is unbalanced in length, thereby causing a phase difference (in time) between the A and B lobes and the field pattern switches continuously right and left of the electrical centre of the aerial system.

At the same time synchronized switching at the indicator enables the signals from A and B to be displayed side by side for the purpose of comparison, so that the appearance on the indicator is similar to that shown in Fig. 30. This effect may be

FIG. 30. APPEARANCE OF SIGNALS AT INDICATOR.



obtained by using an indicator arranged for a type " B " display (as described in a later paragraph), together with synchronized switching of the inputs to the cathode ray tube.

Aerials

The type of aerial employed depends primarily upon the carrier frequency employed and also upon the application. The required beam dimensions are determined largely by the application and when this has been decided upon, the type and size of the radiator, or reflector, as distinct from the aerial, can then be selected. The dimensions of the aerial are, of course, fixed by the carrier frequency employed.

In general, aerial systems used for long-range warning sets are formed by stacked dipoles, with solid, perforated or rod reflectors. In this case the horizontal or vertical directivity of the beam is determined by the number of dipoles stacked in horizontal and vertical planes. The larger the number of dipoles stacked end to end in width or one above the other in height, the narrower becomes the beam in that plane.

For wavelengths of the order of 10 cms., parabolic reflectors become practicable in size and weight. For frequencies at which a coaxial feeder is used, a dipole and reflector are employed to flood the radiator with R.F. When a wave-guide feeder is used, the end of the waveguide may be flared to match the R.F. energy in the guide to free space, but more often the flare is made comparatively small, and positioned in such a manner that it floods a radiator of design suitable for production of the required beam.

All radiators whether for long-range warning sets or for precise measurement are arranged for rotation. Some rotate through a limited arc only, but in the majority of cases they are arranged to rotate through 360 degrees. When a P.P.I. display is used they must be capable of continuous rotation. (The P.P.I. display is described in later paragraphs dealing with indicators.)

In addition to rotation in a given plane, aerials designed for Radar sets used for airborne targets, must also be capable of being tilted to an angle of about 45 degrees.

RECEIVERS

Radar receivers are generally of the superheterodyne type. The essential requirements are that they should be sensitive (minimum sensitivity being of the order of 1 microvolt per metre at least), the signal to noise ratio should be high, the band width of the I.F. stage should cover the video frequency range and all circuits must be designed for minimum distortion.

When automatic gain control is applied to a Radar receiver, it is essential to be able to apply it to one particular selected signal and not to any others that may be present. This is necessitated by the fact that fading of signals from one direction is generally different to that which may be experienced from others. In order to comply with this requirement, arrangements are provided whereby the operator can move a control to select and track any given echo. Manipulation of the control causes automatic gain control to be applied to the particular echo which is being tracked.

It is now generally recognized that automatic frequency control is also essential. This particularly applies to precision measuring sets, in which waves of the order of 10 cms. and below are employed.

Any small change in frequency of either the local oscillator or of the transmitter frequency affects the beat frequency and hence the voltage developed across the I.F. input circuit. Signals passed to the I.F. circuit are generally very small in magnitude at ultra high frequency, and therefore, any reduction on the beat signal applied to the I.F. input cannot be tolerated. In order to avoid such losses, arrangements are made to maintain the beat frequency constant by automatically adjusting the frequency of the local oscillator, to compensate for any change in beat frequency due either to a change of frequency of the local oscillator itself or to a change in the output from the transmitter.

Essential Requirements

The requirements of a high degree of sensitivity and high signal to noise ratio are easily understandable. If the received echo is weak, or if the signal to noise ratio is abnormally low, the echo becomes indistinguishable, with any degree of accuracy, from irregularities on the trace caused by receiver noise (grass). It is also obvious that the ability of a receiver to make use of the minimum possible signal determines the extreme range of useful echo signals for any given transmitting power. Thus, it is evident, that the efficiency of the entire system depends to a greater degree upon the sensitivity and efficiency of the receiver than upon the power output from the transmitter. In other words, it is easier and more efficient to obtain useful range by improving the performance of the receiver, rather than to increase the power of the transmitter.

Since the R.F. envelope of energy radiated is rectangular in shape, it follows that the echo which returns takes the same form. It is also clear that a well-defined leading edge is desirable in order that accurate measurement along the trace to the leading edge of the transmitted pulse may be made. The analysis of a square wave shows that it is composed of an infinite number of sine waves of different frequencies and phases, wherefore the frequency band required to pass a square wave, undistorted is, in theory, infinite.

In practice, however, it is possible to tolerate conditions which are less severe, and it is generally accepted that a band width of from 1 cycle per second to approximately 2 megacycles is sufficient to pass a reasonably square wave. This corresponds

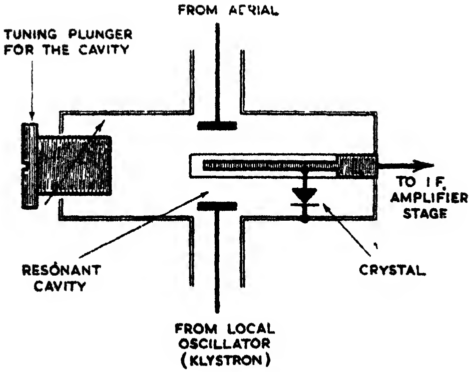
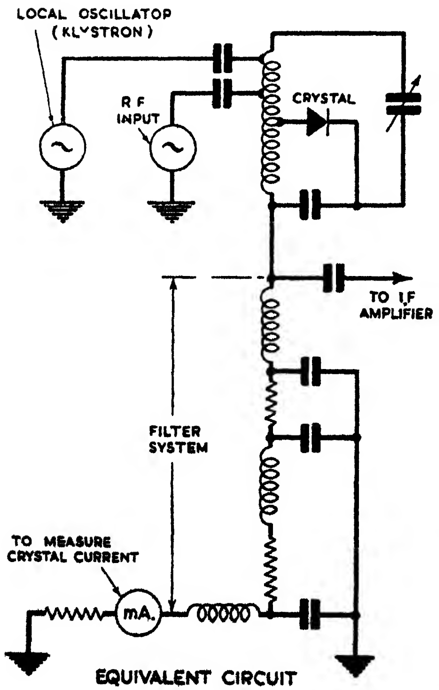


FIG 31A (*left*)—CRYSTAL MIXER IN A RESONANT CAVITY.

FIG 31B (*below*) EQUIVALENT CIRCUIT FOR CRYSTAL MIXER IN A RESONANT CAVITY.

Illustrated in terms of resistance, inductance and capacity.



roughly to the requirements of Television. In consequence of this the I.F. stage must be designed to pass a suitable band of frequencies within these limits. A complication arises, however, because the signal to noise ratio of a receiver falls as the band width is increased, and rises as the band width becomes narrower, the result of this is that the best possible compromise must be effected, having regard to the application for which the particular set is designed. For example, since accuracy of measurement is not the most important requirement for long-range warning sets, a narrower band width can be tolerated in order to increase the signal to noise ratio, and so to promote the efficiency of the receiver. When very precise measurement is required, the band width must be such that an undistorted pulse envelope is passed. In this case the signal to noise ratio of the receiver

falls and therefore the need arises for a stronger echo to enable it to be clearly distinguished from the noise (grass). Grass in Radar terminology is applied to the fringing of the trace produced by noise voltages in the receiver.

From that which has already been said about square waves, it follows that all amplifier circuits in the receiver must be designed to pass a square wave with minimum distortion. The output from the receiver is at video frequency.

In cases where it is necessary to render the receiver inoperative during the transmission period, in order that it may be in a condition to receive echoes from nearby signals immediately after transmission has ceased, a pulse may be provided, either to increase the negative bias on—say—the first two valves of the intermediate stage during the transmission period, or the H.T. may be removed from the anodes of these valves during the pulse time of the transmitter.

When the signal to noise ratio falls below a ratio of 1 : 1, as it tends to do with increase of frequency, R.F. amplification is abandoned altogether, since it only tends to aggravate the trouble. At the higher frequencies, therefore, the I.F. is obtained by causing the output from a klystron, used as a local oscillator, to beat with the received R.F. Mixing is performed by a crystal operating in a resonant cavity. This arrangement is shown in Fig. 31, where it will be noted that the equivalent circuit shows a resonant cavity acting as a parallel resonance-tuned circuit.

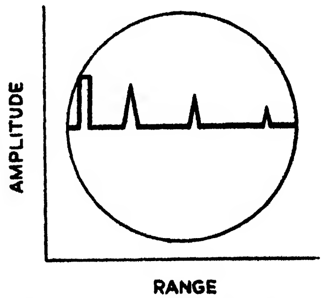


FIG. 32.—APPEARANCE OF THE "A" DISPLAY.

The frequency of the klystron can be controlled, within narrow limits, by the voltage on its repeller electrode and this is the method adopted when automatic frequency control is applied.

Display Units or Indicators

The three principal forms of display are as follows :—

The "A" Display.—This is similar to that which has already been described. In this case amplitude is plotted against time on the cathode ray tube screen. The time base voltage is

applied to the " X " plates and the receiver output is applied to the " Y " plates, the general form of the display is as shown in Fig. 32.

The " B " Display.—In this display, the Time Base may be applied to the " Y " plates and a voltage proportional to the bearing of the aerial is applied to the " X " plates. The output of the receiver is applied to the grid of the cathode ray tube to modulate the brilliance of the beam. In this arrangement the beam scans the whole area of the screen in comparative darkness

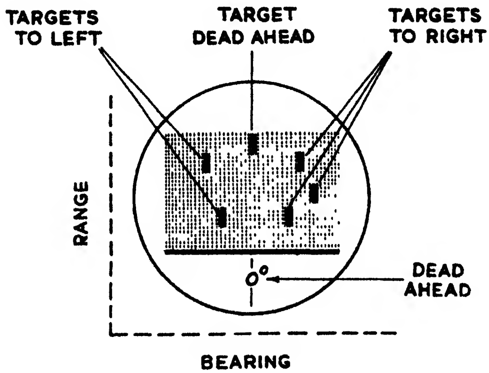


FIG. 33. APPEARANCE OF THE " B " DISPLAY.

In this display range is plotted against bearing.

until an echo is received. The arrival of an echo intensifies the beam, and a bright spot appears on the screen at the position taken up by the beam at that instant (Fig. 33). Since the beam scans the screen under the combined influence of the time base voltage and the bearing voltage, the point at which the spot appears indicates the range and bearing of the target at that instant, with regard to some fixed reference mark. In this display, therefore, range is plotted against bearing.

The P.P.I. Display.—The P.P.I. display presents, in polar co-ordinates, a map of the area being covered, with the aerial occupying the centre of the screen The cathode ray tube is intensity modulated. The time base sweep moves from the centre radially outward. The position of the radial time base sweep is controlled by, and synchronized with, the aerial position through 360 degrees of rotation. The top of the screen represents dead ahead. If the aerial is pointing dead ahead, the sweep moves from the centre of the screen to the top. Likewise if the aerial points 90 degrees from dead ahead, the sweep of the time

base moves from the centre, radially outwards, at an angle of 90 degrees to the right of dead ahead. Thus a polar map is developed on which range is plotted radially against bearing through 360 degrees. This type of display is applied largely to search, harbour control, convoy keeping, ground controlled interception and navigation. The appearance of the display is shown in Fig. 34.

Accurate Range Measurement

Since a given range may be represented by the total length of the time base trace, the range of a target may be estimated by observing the fraction of the trace between its commencement and the leading edge of the echo. Estimates of this kind, however, depend upon the judgment of the operator, even when a transparent, sub-divided scale is supplied. It has also been pointed out that this does not allow for any non-linear rise in the time base voltage or any changes that may take place in the constants of the time base circuit itself from time to time.

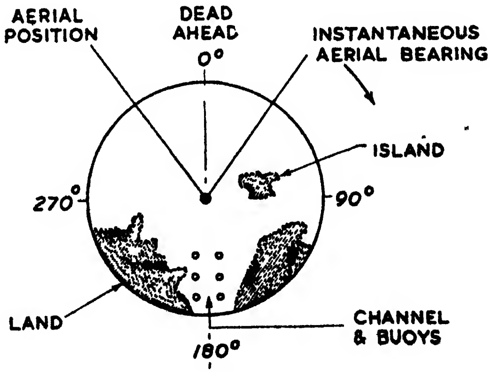


FIG. 34.
APPEARANCE OF THE "P.P.I." DISPLAY.

A type of display which is used for searching, harbour control, convoy keeping, ground-controlled interception and navigation.

It is, therefore, usual to provide a circuit which generates under the control of a synchronizing pulse, very short pulses at regular intervals—corresponding in time perhaps to 1,000 yards. These pulses are mixed with the receiver output on the "Y" plates, in the case of an "A" display and appear as bright marks at intervals corresponding to 1,000 yards along the trace. If a transparent, sub-divided scale is supplied, the 1,000-yard marks on the scale should coincide with the 1,000-yard marks on the trace. If this is not the case, the speed of the time base sweep

must be altered by an adjustment provided until they do correspond. The general process of lining up is termed " calibrating " and the circuit performing this function is known as the " calibrator."

For precise measurement this method is not sufficiently accurate, since it still becomes necessary for the operator to interpolate for intermediate readings. The accuracy with

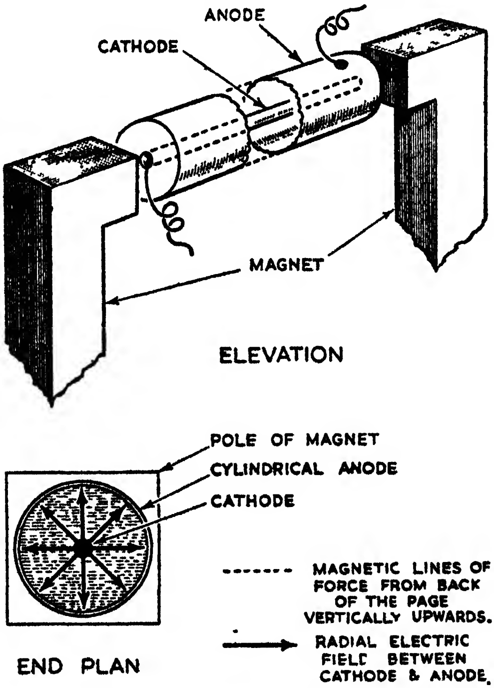


FIG. 35.—ELEMENTARY MAGNETRON.

which this is performed varies with the individual. Therefore, when precise measurement is required to within a few yards, other means are provided for this purpose. One method, which gives reasonably satisfactory results, is to compare the time base voltage, measured at the instant of time that the echo is received, with the voltage of a standard, calibrated potentiometer. In practice this is carried out by moving a control until a mark—usually a bright spot called a strobe or movable range-marker, appears super-imposed upon the echo to be measured. The movement of the control causes the voltage of the sweep at

that instant to be compared with that of a standard calibrated potentiometer, the control moved by the operator is gauged with the slider of the potentiometer, consequently, the range can be read off directly from a calibrated scale, over which the pointer attached to the slider of the potentiometer travels. Other more accurate methods are also available.

Various types of indicators have other refinements. For example, it is possible to select the small portion of trace containing an echo in which the observer is interested, and to expand this small fraction so that it covers the entire width of the screen. This permits examination of the particular echo in detail, and without distraction by other echoes which may be present at the same time. It also has other beneficial results. In the case of a plane on interception duty the observer may be provided with a "B" type display on which, by manipulation of the Radar controls under direction of R.T. from the ground, the target can be displayed. In order that the pilot may follow the target without distraction, the observer can select from his display on the "B" indicator the portion containing the target of interest and cause a reproduction of this portion to appear on the display unit situated at the pilot's position. This type of display is termed a selected range display.

THE RESONANT MAGNETRON

The resonant magnetron is a development of the split anode magnetron and the original magnetron which first appeared about 1924. In its present form, it is now almost universally employed for generating R.F. at frequencies corresponding to wavelengths of the order of 10 cms. or less. Since the resonant magnetron embodies, in some form or another, all the phenomena peculiar to the original magnetron and to the split anode magnetron, the original magnetron and the split anode magnetron may be regarded as special cases of the resonant magnetron.

All magnetrons are, basically, a type of diode in which a magnetic field is established parallel to the axis of the anode, and perpendicular to the normal electric field between cathode and anode. This field is generally established by means of a permanent magnet, between the poles of which the diode is placed, see Fig. 35. It is essential that the magnetic field should be uniform over the whole of the cathode–anode space. In

the absence of a magnetic field the device behaves as a normal diode. If the value of the H.T. is fixed, however, and the magnetic field strength varied, the curve shown in Fig. 36 is obtained, from which it will be seen that the anode current remains steady as the magnetic field is increased until the point X is reached, when the current suddenly drops towards zero. This is the critical or "cut off" value of magnetic field for the fixed value of H.T. A similar curve can be obtained if the magnetic field is fixed at some given value and the H.T. varied.

An aggregate of electrons in motion is comparable to an electric current flowing in a conductor, consequently when electrons emitted from the cathode are accelerated towards the anode by the electric field they experience a force, due to the transverse magnetic field, which acts at right angles to their direction of motion and to the direction of the magnetic field. Application of Fleming's left hand rule in Fig. 35 indicates that the electron tends to move upwards through the paper and that as the deflecting force is continuous, the curvature of the path is progressive, so that the orbit of the electron tends to become circular.

Thus in Fig. 36(*a*) the magnetic field is not strong enough to make the radius of curvature such that the electron misses the anode. In Fig. 36(*b*) the magnetic field has been increased, the radius of curvature increases and the electron just misses the anode. In Fig. 36(*c*) the magnetic field is further increased

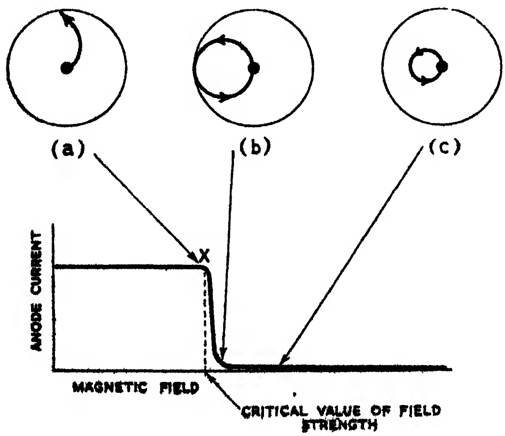


FIG. 36.—EFFECT OF MAGNETIC FIELD STRENGTH ON ELECTRON ORBITS AND ANODE CURRENT.

All these diagrams are as viewed when looking into one end of the Cylindrical Anode as in end view Fig. 35.

and the effect upon the radius of curvature of the electron path is very marked.

Electrons going from cathode to anode are accelerated by the electric field and therefore receive energy from it. Electrons which are turned back towards the cathode are obviously moving against the force exerted upon them by the electric field and because they are doing work on the electric field they must be surrendering energy to it and therefore to the anode. If an oscillatory circuit is now connected between anode and cathode, oscillations can be generated, the time period being equal to the transit time of the electron (the time taken for the electron to go from and return to the cathode, Fig. 37).

The Split Anode Magnetron

If the anode is split, the two halves being joined by an oscillatory circuit as shown in Fig. 38, R.F. set up in the oscillatory circuit causes the segments 1 and 2 to become alternately positive and negative, and there is an alternating electric field due to this across the gaps between the segments. This R.F. field tends to turn the radial electric field through a small angle (Fig. 39) so that when the values of magnetic field strength and H.T. are

FIG. 37 (right.) ELEMENTARY MAGNETRON ARRANGED AS AN OSCILLATION GENERATOR.

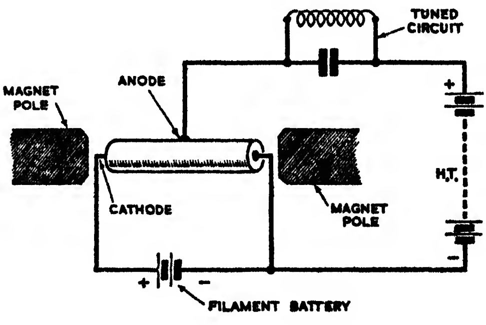
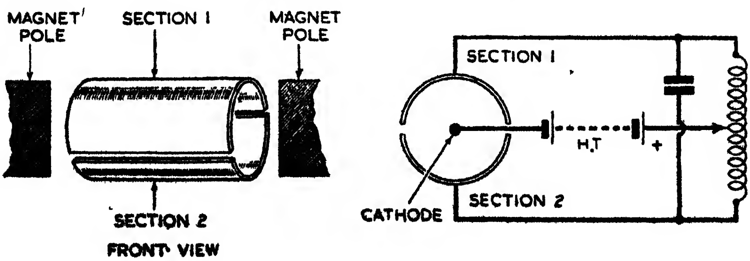


FIG. 38 (below). DEVELOPMENT OF THE SPLIT ANODE MAGNETRON. Diagram showing the basic anode construction and oscillatory circuit.



adjusted well below cut off, the modification of the radial field, due to R.F. on the anode, is such that electrons approaching the gap (normally missing the anode) are urged by the distorted field towards the segment of lowest potential and caused to land upon it. This constitutes a generating effect, or static negative resistance which is always associated with the segment which happens to be at the lowest potential. (Fig. 40).

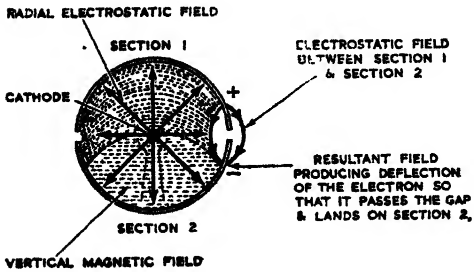


FIG. 39.—DISTORTION OF THE ELECTRIC FIELD BY THE R.F. FIELD.

The frequency of the oscillations set up in the oscillatory circuit is determined by the frequency of the oscillatory circuit. The power output is greatly increased due to the fact that there is a nett loss of electrons from the cathode to the anode, which must be replaced by the H.T. It will be noted from Fig. 40 that the path followed by a single electron from cathode to anode would now be spiral in form.

Construction of the Resonant Magnetron

The anode of a resonant magnetron consists of a solid block of copper in which the resonant elements, formed by a combination of hole and slot, are incorporated. The number of elements may be from 8 to 16 or 18 ; an even number is essential. The cathode, with a diameter usually about half the bore of the anode, is constructed from a nickel mesh, to which is keyed an oxide coating. End shields prevent electrons escaping to the anode from the cathode without first interacting with the magnetic field. The end blocks, due to the raised rim on which they rest, do not make close contact over the

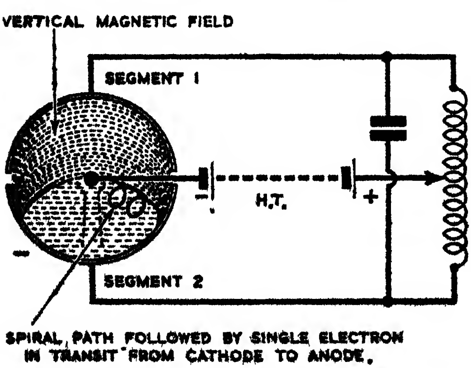


FIG. 40.—SPIRAL PATH OF A SINGLE ELECTRON.

whole of the anode surface and there is, therefore, an air gap between end block and anode through which the fields of the respective cavities are coupled together. A gold ring is sandwiched between the anode rims and the end blocks, so that when the valve is on the pumps and at high temperature, the gold fuses into the copper and forms a seal which is vacuum tight. It will be noted that some of the anode segments are strapped together, this greatly improves the frequency stability of the device.

The output is taken via the coupling loop from the resonant cavity in which it is situated. As all the cavities are linked together by their fields in the manner described above, it is only necessary to have one output connection. The coupling loop is taken out through the glass seal by a suitable extension, and a screwed connection is provided for the outer sheath of a coaxial cable. The input terminals carry the heater current, and the cathode is joined to both legs internally. Cooling fins are provided to facilitate heat dissipation from the anode.

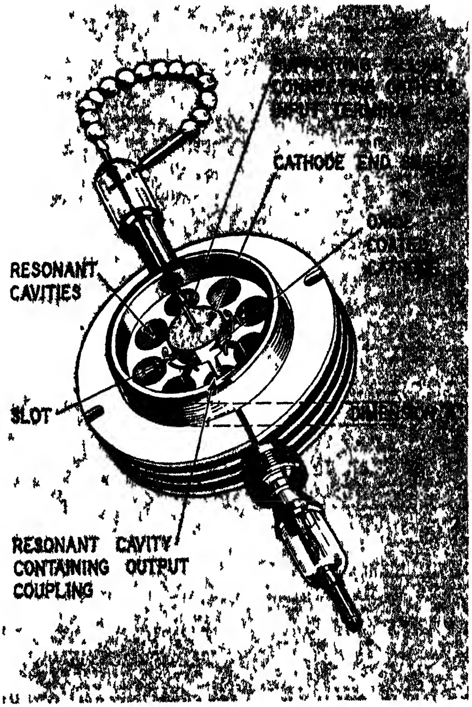


FIG. 41.—CONSTRUCTION OF THE RESONANT MAGNETRON.

The heater current for a certain type may be about 1¼ amps., the cathode emission is of the order of 40/50 amps. per sq. centimetre and the peak voltage pulse of about 1 microsecond is of the order of about 14 kV. The output of this type of valve is about 120 kilowatts for a 1-microsecond pulse at a frequency corresponding to approximately 10·5 cms.

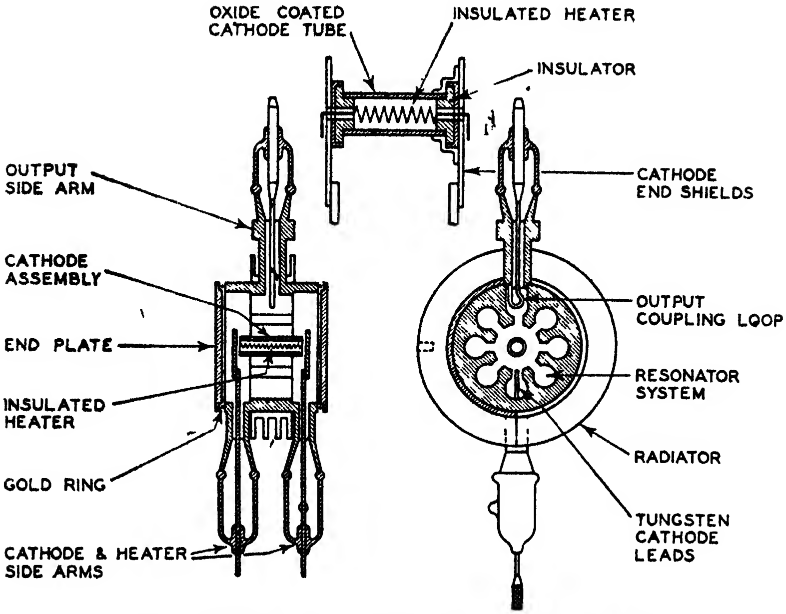


FIG. 42.—ESSENTIALS OF A MULTI-RESONATOR MAGNETRON.

Analogy illustrating the General Principle of Operation

Let it be assumed that a number of empty jars, similar in size, form and material are arranged in a circle, with all mouths pointing inwards, and that an electrically driven fan is arranged to blow a current of air over the mouths of the jars. The air currents passing over the mouths of the jars, will, under favourable circumstances, cause air vibrations within the jars to produce a resonance within them.

A large amount of energy due to these vibrations is now available in the jars, consequently, if this energy can be transferred efficiently to some device, matched to the frequency of the air vibrations, the energy built up in the jars by the resonance effect can be utilized and made to do a proportionately large amount of work.

Since, under *no load* conditions, a very small amount of energy is taken from the air currents in order to establish and build up the state of resonance in the jars, provided that the losses in the jars are low, a comparatively large amount of energy can be built up for a relatively small power input. The

energy for maintaining oscillations under loaded conditions, however, must make good the losses in the resonant cavities, and would therefore be supplied by the fan and the power source which drives it.

If for the jars, the air current and the fan of the analogy, the cavity resonators, the electron movements and the source of high voltage, respectively, are substituted, it can be seen that the function of the electrons of the spare charge is twofold. (*a*) To excite and build up oscillations in the resonant cavities at the required frequency and in the desired mode and (*b*) to maintain these oscillations by making good the losses incurred under loaded conditions.

Initially, the values of the magnetic field and the H.T. are adjusted well below the cut off point, so that no electrons can reach the anode without the help of R.F. The path of a single electron from cathode to anode is shown in Fig. 43. The looped path and the abrupt changes of direction may be accounted for in the following manner. A number of electrons in motion may be thought of as an electric current, the strength of the current being proportional to the velocity of the electrons. Since a conductor carrying a strong current experiences, in a magnetic field, a stronger deflecting force than a conductor carrying a weak current, electrons of high velocity experience a greater

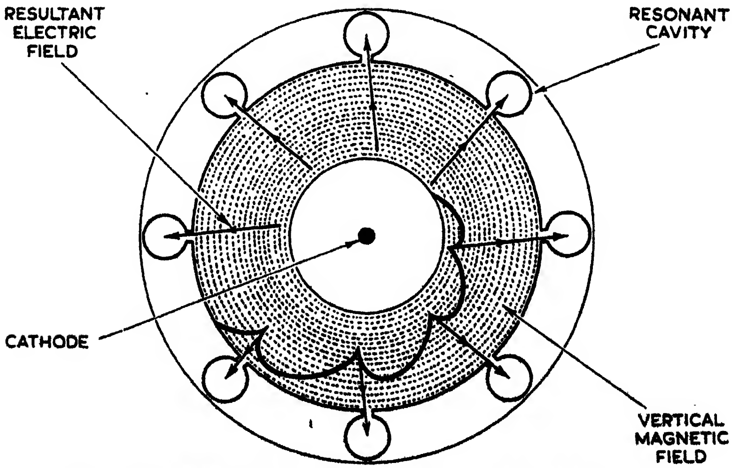


FIG. 43.—CROSS-SECTION OF THE RESONANT MAGNETRON.
The path of a single electron is illustrated.

deflecting force from a transverse magnetic field than do electrons of low velocity moving through the same field. Thus, when the electrons are turned back towards the cathode by the action of the magnetic field, since they are moving against the electric field, their motion is retarded and they are slowed down, momentarily coming to rest. In this condition, the magnetic field has no effect upon them at all and, therefore, the electric field again tends to accelerate the electrons towards the anode. This action causes the magnetic field to exert its deflecting force once more, and so the sequence is repeated, until the electron approaches the anode so closely that it is finally landed on the low potential segment of one of the pairs of segments containing a resonant cavity.

The Anode Wave System

If the output from an oscillation generator is applied to the anode of a resonant magnetron, when the latter is unloaded, a series of voltage patterns can be observed on the face of the anode as the frequency of the oscillation generator is changed (Fig. 44). As the frequency is increased, pattern (*a*) will disappear and at some slightly higher frequency pattern (*b*) will appear and so on. These patterns indicate the mode in which the magnetron is oscillating and are designated by the number of maxima which can be counted in going once round the anode, (e.g. pattern (*a*) $n = 4$). This means that the magnetron can oscillate at any, or all of these frequencies, by suitable adjustment, and that more than one of these modes can exist at the same time. Since it is undesirable that the magnetron should oscillate in more than one mode at a time and because the loading is generally insufficient in itself to discriminate against unwanted modes in the output, strapping has been resorted to, in order to separate the modes more widely. The underlying principles of strapping and the requirements for efficient operation of the magnetron are associated with considerations of the space charge.

Examination of the path of a single electron and of the space charge indicates the existence of a resonance velocity, and affords some idea of the principle upon which the resonant magnetron operates. It is not possible, however, in a brief survey to attempt any detailed description of the operation of this fixed frequency valve.

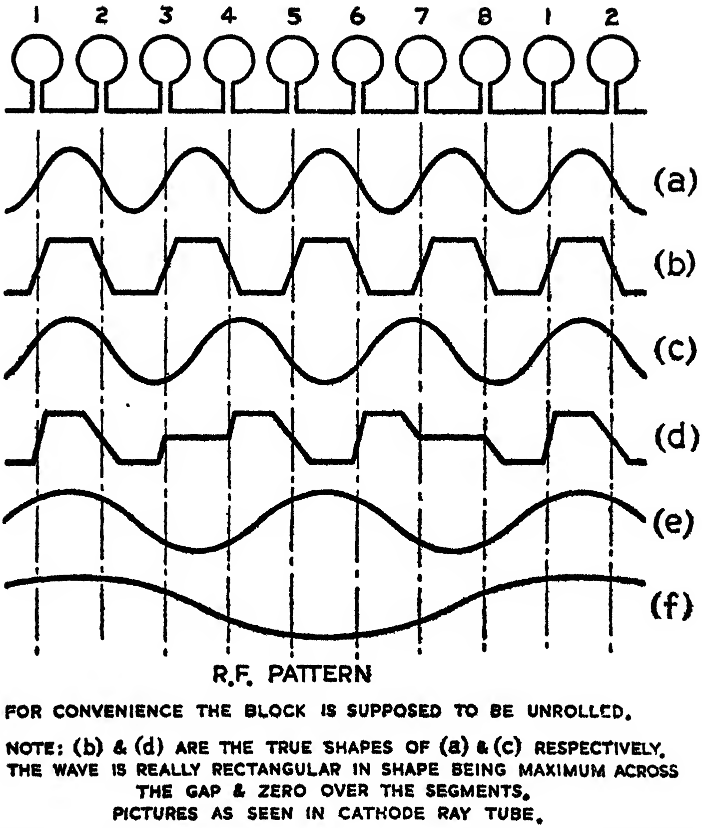


FIG. 44.—ANODE VOLTAGE PATTERNS FOR A RESONANT MAGNETRON OF 8 CAVITIES.

Summary of Operation

The following is a brief summary of the operation of the resonant magnetron, ignoring the effect of the space charge :

(*a*) The valve is operated with the initial adjustment of Va and H well below cut off.

(*b*) A state of instability following immediately upon switching on, causes an oscillation to take place in the anode resonant circuit.

(*c*) The R.F. field resulting from (*b*) causes some electrons to be retarded, and therefore, to give up energy to the resonant circuit. This energy is used to build up the oscillation.

(*d*) Other electrons are accelerated, in consequence, they are acted upon by the magnetic field more strongly, and turned back

to the cathode before they can absorb much energy from the R.F. field.

(*e*) Electrons which are retarded proceed along looped paths to the anode. During transit they acquire energy due to angular velocity and surrender energy in the form of radial velocity.

(*f*) Thus, during transit, they build up oscillations by virtue of the energy which they surrender to the anode resonant circuits (loss of radial velocity), and on arrival at a low potential segment, in time phase with the R.F. energy, make good losses in the resonant circuits by the net gain of energy from the H.T. source, which they represent.

THE REFLEX KLYSTRON

The reflex kylstron is used as a local oscillator for generating frequencies of the order of 3,000 megacycles or more. Its power output is small, but this serves to beat with incoming signals. When the inputs from the incoming signal and the local oscillator are applied to a crystal mixer, the output, which is the frequency difference, is applied to the initial stages of the I.F. amplifier—which may be remote from the receiver proper and frequently situated close to the aerial.

The reflex klystron is known as a velocity modulated valve, a cross section of which is shown in Fig. 45.

An electron beam emitted by the cathode C is accelerated by the D.C. potential of the grid. Some of the beam electrons pass through a hole into the resonator. Assume that for this reason the resonator is in an oscillating state, the inside of the resonator can be regarded as a tuned circuit of high " Q ", the inductance being the path from *a* to *b* and the capacity being across *ab*.

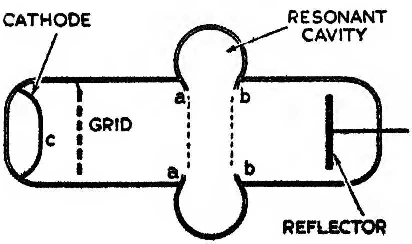


Fig. 45.—Cross-section of the Reflex Klystron.

There will be an alternating R.F. field between *a* and *b*, and the electrons comprising the beam in their passage across the path *aa*, *bb*, will be made to travel faster or slower, according to whether they are accelerated or retarded on entering the R.F. field. This results in the charged particles

being bunched into groups of varying density, since the density of the beam is changed or modulated by varying the velocity of its electrons. The beam travels on until it comes near to the negatively charged repeller, where it is turned back and travels into the resonator gap again. If the length of the path from the resonator to the arm and back and the velocity of the beam (depending upon the accelerating voltage) are properly adjusted, the groups return to the gap *aa*, *bb* when the phase of the field at *aa* and *bb* is so related to the time of their passage that energy is extracted from each group, the total nett gain of energy acquired by the resonator being sufficient to maintain oscillations and to supply the load. The resonator having the properties of a high magnification circuit—i.e. a high value of "Q," the frequency remains very stable after the valve has been given time to warm up.

Principle Functions

The action of the reflex klystron may therefore be resolved into two major functions—(1) A bunching operation and (2) an operation in which there is a nett delivery of energy to the R.F. resonant cavities. Operation 1 may be regarded as an incidental but essential operation enabling Operation 2 to be carried out.

Since R.F. is assumed to have been excited in the resonant cavities by shock or transient, the electric field in the region *aa*, *bb*, is alternating in character. The electron beam enters this region, due to the gun action of the accelerating grid, in consequence of which, electrons are either accelerated or retarded, according to the phase of the R.F. at any instant of time.

Those which are retarded do work on the electric field *aa*, *bb*, and, therefore, contribute energy to the resonant cavities, whilst those which are accelerated have work done upon them by the electric field and, therefore, absorb energy from it. On balance therefore, apart from the losses in the cavities, there is neither gain nor loss of energy from this operation. But, whereas the beam enters

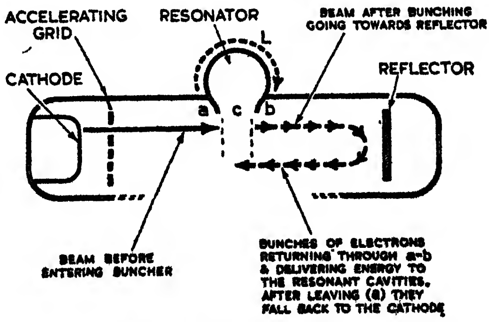


FIG. 46.—PRINCIPLE OF THE REFLEX KLYSTRON.

the area *aa*, *bb* as a steady stream of electrons, it emerges as a series of detached groups of electrons with a time interval between each group, equal to one half cycle of R.F.

Since the mirror or repeller is negatively charged, electrons emerging from the bunching operation are, at some point, turned back towards the cathode, and are forced to pass again through the area *bb*, *aa*.

On the return journey conditions are very different from the outward journey, because the groups, gaps between them, and the phase of the R.F. may all be such that *all the electrons in all the groups are retarded.* In this case, the energy which the returning electrons receive from the repeller may be extracted as a nett gain by the resonant cavities during the return journey, and there is therefore an *overall gain of energy by the cavities.*

INDEX

" A " display, 663
A.C.—
  circuit calculations, 235
  commutator motor, 89
  motors, 79
  motors, starting, 91
  receivers, 439
  resistance, calculating, 237
A.C./D.C. receivers, 450
Acceptor circuit, 368
Accessories, circuit, 477
Accumulators, 438, 463
  alkaline, 468
  alkaline, charging, 476
  initial charge of, 470
  jelly acid, 475
  maintenance of, 469
  trouble, 472
Aerial(s)—
  Adcock, 599
  amplifier relay system, 144
  anti-interference, 462
  arrays, 505
  Belling-Lee system, 462
  Bellini-Tosi, 598
  centimetre range, 634
  cheese, 634
  dipole, 499, 568, 583
  F.M. system, 143
  long-range warning sets, 633
  loop, 592
  open, 597
  systems, 144, 462, 499
  television, 583
  transmitting, television, 508
After-glow, 530
Air-cored transformer, 332
Airborne sets, radar, 619
Aircraft—
  detection of, 629
  direction finding, 600
Alexandra Palace, 557
  transmitter, 565
Alkaline accumulators, 468 476
Alternator principle, 41
Amateur experiments, 132
American valves, 291
Ammeters, 106, 113, 115
Ampere, 19, 102
Amplification—
  audio-frequency, 276
  Class A, 400
  Class AB, 406
  Class B, 320, 404
  curves, 205
  factor, 264, 303, 335, 389
  low-frequency, 385, 484
  push-pull, 141, 320, 401
  radio-frequency, 329, 366
  valve, 388
Amplified A.V.C., 383
Amplifier—
  intermediate frequency, 285
  radio-frequency, 276
  relay system, aerial, 144
  selenium bridge, for, 545
  triode as, 267
Amplitude—
  distortion, 338
  distortion, transformer, 205
  modulation, 137
Analogy—
  anode load, 266
  beam tetrode, 315
  cathode-ray tube, 26
  push-pull, 402
  reservoir, 17
  wave, 124, 136
Angular frequency, 250
Anode, 22
  bend detection, 346
  bend detector, 296, 305
  current variations, 330
  dissipation, 398
  feed resistances, 161
  load, 266, 332
  phantom, 292
  resistances, 160
  tuned, 278, 479
  voltage, patterns, 675
Anodising, 100
Anti-interference aerials, 462
Aperiodic choke, 332
Arc—
  furnaces, 61
  lamps, 64
  welding, 61
Arm, tracking, 436
Armature, 46
Arrays, aerial, 505
Artificial line, 646
Astigmatism control, 587
Atom(s), 12
  bomb, 9
  helium, 13
  hydrogen, 13
  splitting the, 9
Atomic—
  energy, 34
  number, 14
  piles, 34
  structure, 13
  weight, 14
Audio-frequency—
  amplification, 276
  amplifier valve, 310
  transformers, 204
Auto—
  choke coupling, 210
  electronic emission, 55
  synchronous motor, 89
  transformer, parallel feed, 395
  transformers, 92, 95
Automatic—
  frequency control, 660
  gain, 660
  starter, 78
  tuning devices, 374
Automatic volume control, 308, 377, 483, 570
  amplified, 383
  delayed, 309, 345, 381
  filter circuit, 381
  quiet, 384
  voltage, applying, 379
AvoMinor, D.C. testmeter, 112

" B " display, 664
BH curve, 185
Back-e.m f., 74
Background noise, 371
Baffles, 417
Bakelite, 223
Bandpass—
  coupling, 281
  filter, 369, 479
  tuning, 211, 338
Bands, side, 138, 368
Barium, 537
Barretter, 452
Barrier layer photocell, 546
Bases, time, 493, 521, 559, 577
Batteries, 438
Beacon(s)—
  ground, 605
  stations, radar, 620
Beam—
  constants, 631
  distribution loudspeaker, 419
  Empire, system, 508
  forming plate, 314
  splitting, 632
  switching, 658
  tetrode analogy, 315
  tetrode valve, 314
  widths, 630
Beaming by arrays, 506
Bearing(s)—
  measurement of, 626
  swing, 593
Beat—
  frequencies, 358
  interference, 376
Becquerel—
  effect, 536 549
  Henri, 549
Belling-Lee aerial system, 462
Bellini-Tosi aerials, 598
Bias resistance, 290
Biot, 101
Black spotter, 573, 587
Bleeder resistor, 324
Block diagram, superhet. receiver, 362

Boosters, 93
Bridge—
circuit, 447
connected, full wave rectifier, 97
Broadcast relay systems, 144
Broadcasting, 123
Butt welding, 60

Cables, co axial, 655
Caesium, 537
Calibration—
generators, 637
screen, 621
time base, 623
Calibrator, 666
circuit, 638
Camera, electron, 552
Campbell Swinton, 517, 552
Canister, screening, 368
Capacitor charging curve, 560
Capacity, 31, 215
choke, H F, 176
inter electrode, 335
specific inductive, 221
Car radio, 484
Carbon microphones, 424
Cardioid diagram, 596
Carrier—
frequency separation, 138
radio frequency, 341
wave, 135
Cartridge type resistance, 166
Cathode ray tube, 25, 517, 553, 604, 620
double beam, 530
hard, 528
high voltage, 531
mechanical analogy, 26
miniature, 532
modulation, 576
power supplies, 532
Cathode(s), 22
follower circuits, 406
heater circuits, 449
valve, 59
Cavity, resonant, 657, 673
Cell(s)—
alkaline, 468
dry, 38
electrolytic, 99
lead-acid, 463
Leclanché, 37
primary, 36
secondary, 463
selenium-iron, 547
Centimetre range, aerials for, 634
Centre-tapped—
resistance, 174
transformer, 402
Changing, frequency, 361
Channel—
selectivity, 359
vision, 557
Characteristic—
curve, triode, 263
variable-mu, 284
Charge—
condenser, 27
electric, 11, 15
Charging—
alkaline accumulators, 476
curve, condenser, 523, 560
process, 467
Charts, 150
hyperbolic, 610
lattice, 611
wavelength and frequency, 155
Cheese aerial, 634
Choke(s)—
aperiodic, 332
capacity coupling, 179, 190
closed core, 198
frequency, 175
gapped core, 197
high impedance, 337
low frequency, 189
mains lead, 178
output filter, 193
short wave, 178
smoothing 195
tapped output, 193
tone control, 194
Chromel alumel, thermo couples, 49
Circuit(s)—
acceptor, 368
accessories, 477
bridge, 447
calibrator, 638
cathode follower, 406
F M receiver, 142
neutrodyne, 335
television, receiver, 569, 574
time base, 521
tuned, 245, 332
vibrator, 485
video, 573
Clark Maxwell, 27, 130
Class—
A amplification, 400
AB amplification, 406
B amplification, 320, 404
Closed core chokes, 198
Co axial cables, 655
Code, Morse, 135, 497
Coercive force, 185
Coil—
inductance, formulæ, 231
induction, 135, 230, 517
speech, 414
tuning, 256, 336
Coiled filament, 64
Cold emission, 55
Cold-cathode rectifier, 324
Colour code, wander plugs, 439
Commutator, 46
Compasses, radio, 603
Compensator, power factor, 117
Compound, 13
Compound-wound—
dynamo, 48
motor, 73, 77
Compression, volume, 408
Concentric feeders, 499, 584
Condenser(s), 215
capacity calculation, 220
charge, 27
charging curve, 523
differential, 220, 227
drives, 226
electrolytic, 228
fixed, 228
gang, 225, 366
impedance, 242
log, law (log line), 217
microphone, 140, 246
split end plate, 225
square law, 216
straight line capacity, 216, 227
straight line frequency, 217
variable, 223
Conductance—
conversion 288
mutual, 265
Conduction, 19
electronic 20
gas in, 23
liquids, in, 20
vacuum, in, 21
Conductors, 18
Contact potential 261
Continuous waves signal frequency, 355
Contrast control, 586
Control—
astigmatism, 587
contrast, 586
focus, 585
linearity, 587
picture hold, 586
pulse, 651
switching, 376
Constants—
beam, 631
radar system, 639
Convection currents, 25
Conversion—
conductance, 288
frequency, 363
wavelength to frequency, 126
Convertors, 92
Copper—
eureka thermocouples, 49
nucleus, 14
Cossor—
double beam tube, 530
41 MTL valve, 264
41 MTS valve, 566
42 O.T.D.D valve, 320
MSG/LA valve, 272
PT41B valve, 316
220 VSG valve, 271
Coulomb, 14
Coupling—
auto choke, 210
bandpass, 281
choke-capacity, 179, 190
L F., units, 209
resistance capacity, 389

Coupling—*contd.*
transformer, 392
tuned grid, 280
Course-setting beacons, 606
Crookes, 517
Cross modulation, 273, 285, 289
Crystal(s)—
detector, 296
frequency, 51
microphones, 247
pick-up, 432
piezo-electric, 247, 420, 432
Currents—
convection, 25
displacement, 27
electron, 52
magnetic effects of, 66
node, 507
polarization, 28
C.W. transmission, 135
Cycle, duty, 642
Cylinder, Wehnelt, 518, 529

Damping, 103, 110
D.C.—
generator, 45
mains resistances, 164
motor, 70
motors, starting, 78
testmeter, AvoMinor, 112
Decoupling resistances, 165, 172
Deflection—
electrostatic, 489
magnetic, 529, 573
symmetrical, 527
Deflector plates, 519
Delayed A.V.C., 309, 345, 381
Demodulation, 341
Density, flux, 182
Depolarizers, use of, 37
Detection, 276, 294, 342, 615
aircraft, 629
anode bend, 346
grid, 348
infinite, impedance, 303
power grid, 351
Detector—
anode bend, 296, 305
crystal, 296
diode, 299, 305, 343
function of, 294.
grid bias, 172
infinite impedance, 305
leaky grid, 301, 306
power grid, 303
stage, 341
stage, television receiver, 572
video, 568
Determination, sense, 595
Dielectric, 221
constant, 223
heating, 63
strain, 29

Difference tones, 355
Differential—
condenser, 220, 227
permeability, 185
Dimming, 625
Diode(s), 98, 257, 259
detector, 299, 305, 343
operating conditions, 346
rectifier, 141
Dipole(s), 499, 568, 583, 633
half-wave, 143
reflector, 583
stacked, 634
Direct ray, 134
Direction finding—
aircraft, 600
radio, 591 *et seq.*
Discharge—
accumulator, 471
lamps, 65
tubes, neon, 373
Discriminator, 140
Displacement current, 27
Display—
"A", 663
"B", 664
P.P.I., 664
units, 663
Dissipation, anode, 398
Distortion, 122, 268, 337, 343, 377
amplitude, 338
harmonic, 312, 316, 396
transformer, 204
Divider, potential, 165
Double—
beam C.R. tubes, 530
diode pentodes, 344
diode triodes, 344
images, 589
Doubler, voltage, 322
Drift, oscillator, 370
Drives, condenser, 226
Dry cells, 38
Dual loudspeakers, 420
Duty cycle, 642
Dynamic—
field, 229
resistance, 202, 277
Dynamo, 45
compound-wound, 48
separately-excited, 48
shunt-wound, 48
Dynamometer instruments, 113

Eddy current—
heating, 62
losses, 392
Edison, Professor, 257
Effect—
Becquerel, 536, 549
photovoltaic, 535, 545
Effective resistance, 237
E.H.T.—
power pack, 581
transformer, 582

Electric—
charge, 11, 15
field, 16
lighting, 64
power, 66
Electrical heating, 57
Electrochemistry, 99
Electrode assembly—
Mazda R.F. pentode, 276
Mazda TH41 triodeheptode, 285
Mazda triode, 263
pentagrid valve, 291
Electrode system, magic eye, 373
Electrodynamic instruments, 113
Electrolyte, 20, 37, 464, 470
Electrolytic—
cells, 99
condenser, 228
Electromagnetic—
damping, 105, 110
deflection, 529
instruments, 108
relay, 69
theory, 495
waves, 591
Electronic conduction, 20
Electron(s), 12, 98
atmosphere, 18
camera, 552
currents, 52
drift, 28
emission, 258
gun, 25
multiplier, 55, 542
Electro-plating, 100
Electrostatic(s), 31
C.R. tube, 517
deflection, 489
voltmeters, 119
Element, 13
Eliminators, 164, 453
Emission—
auto-electronic, 55
cold, 55
electron, 258
field, 35, 55
photocells, 54, 539
photo-electric, 22, 35, 53, 535
secondary, 25, 35, 54, 275, 314, 542
tests, 121
thermionic, 22, 35, 52, 258
Empire beam system, 508
Experiments, amateur, 132
Exponential horn loudspeaker, 421
Extension speakers, 422

Factor—
amplification, 264, 303, 335, 389
magnification, 253
power, 200

Fading, 377
Faraday, 517
Farads, 242
Faure, plates, 464
Feed, parallel, 172, 208, 394
Feedback, 430
  negative, 303, 310, 316, 406, 571
  oscillator, 364
  parallel, 319
  positive, 316, 343, 479
Feeder(s), 499
  concentric, 584
  impedance, 511
  matching, 510
  parallel, 394
  systems, 653
  twin, 583
Field—
  emission, 35, 55
  rotating, 80
Filter(s)—
  bandpass, 369, 479
  choke output, 193
  circuit, A V C., 381
  circuits, tuned, 359
  high pass, 435
  interference, 485
  scratch, 435
Fire control, radar, 619
Fixed—
  condensers, 228
  potentiometers, 169
Fleming's—
  left hand rule, 70, 668
  right hand rule, 40
Fluorescent—
  lamps, 66
  screen, 26, 520
  screen materials, 529, 553
Flutter, 430
Flux—
  density, 182
  meter, Grassot, 183
Flyback, 522, 554, 625
F.M. system—
  aerial, 143
  receiver, 140
Focus control, 585
Focusing, magnetic, 529, 575
Force—
  coercive, 185
  magnetizing, 182
Frame, 555
  scan, 493, 554
  time bases, 579
Frequency—
  angular, 250
  beat, 358
  changing, 284, 361, 482, 570
  chokes, 175
  control, automatic, 660
  conversion, 363
  crystal, 51
  distortion, transformer, 204
  intermediate, 360
  modulation, 138
  oscillators, 51
Frequency—*contd*
  power, 123, 236
  pulse repetition, 640
  radio, 123
  ranges, H F. heating, 62
  resonant, 249
  response, 394
  separation, 342, 359
  stages, intermediate, 481
  supersonic, 358
  time base, 525
Frequency changers, 284
  pentagrid, 291
  pentagrid, mixer, 293
  television receiver, 570
  triode hexode, 285
  triode pentode, 293
Full-wave—
  rectification, 97
  rectifiers, 97, 441
Furnaces, arc, 61
Fuses, 439

Gain—
  control, automatic, 308, 660
  stage, 277, 281
Galvanometer, 102
Gang condensers, 225, 366
Gap, rotary spark, 652, 657
Gapped core chokes, 197
Gase(s)—
  conduction in, 23
  discharge triode valve, 324
  filled lamps, 64
  filled photocells, 539
  filled relays, 524
  ionization in, 15
  tube, 23
Ganging, 169
" Gee ", 609
Generator(s)—
  calibration and range mark, 637
  D C , 45
  magnetron R F , 651
  motor, 456
  push-pull R F., 648
  scan, 555
  self-pulsed R.F., 644
  time base, 621
Graphs, 150
  logarithmic, 128
Grassot flux meter, 183
Grid—
  bias detector, 172
  bias resistances, 162
  bias, variable automatic, 171
  construction, 289
  detection, 348
  drive, positive, 405
  leak, 160, 171, 390
  oscillator, 288
  suppressor, 275
Ground beacons, 605
Gun, electron, 25
Half power points, 632
Half wave dipole, 143
  rectification, 96
  rectifiers, 439
Hard—
  C R tubes, 528
  valve time base, 526
Harmonic distortion, 312, 316, 396
Hartley type oscillator, 644
Heater circuits, cathode, 449
Heating, dielectric, 63
  eddy current, 62
  electrical, 57
  H F, frequency, ranges of, 62
Heaviside, Professor Oliver, 134
  layer, 134, 377, 600
Helium atom, 13
  nucleus, 14
Henry, 231
Heptode valve, 364
Hertz, Heinrich, 28, 131, 135, 536
  transmitter and receiver, 131
Heterodyne principle, 355
Hexode frequency changers, 288
High—
  impedance choke, 337
  pass filter, 435
  voltage C R tubes, 531
High frequency—
  chokes, 175
  response curves, 337
  stage, selectivity, 336
  transformer, 338
  valve stages, 334
Homing system, 601
Horizontal radiation pattern, 627
Horn loudspeaker, 411
  exponential, 421
Hot wire meters, 118
H T supply, C.R. tube, 528
Human ear, sensitivity, 206
Hydrogen atom, 13
Hydrometer, 464
Hyperbola, principle, 610
Hyperbolic charts, 610
Hysteresis, 183
  loop, 184
  loop, subsidiary, 187

Iconoscope, 552
Images, double, 589
Impedance, 237, 247, 264, 266
  condenser, 242
  feeder, 511
  infinite, detection, 303, 305
  low-frequency choke, 241
  transformer, 512
  valve, 338
  vector, 243

Incremental permeability, 185
Indicating instrument, 102
Indicator(s)—
  magic eye, 373
  meter type, 604
  neon tube, 604
  tuneon, 373
  tuneray, 484
  tuning, 372
  visual, 603
Inductance, 191, 229
  calculating, 231
  mutual, 199, 202, 231, 234
  smoothing choke, of, 196
Induction, 229
  coil, 135, 230 517
  meters, 115
  motor slip ring, 85
  motors, 80
  watt-hour meters, 116
  wireless circuits, 233
Inductor type loudspeaker, 413
Infinite, impedance detection, 303
Initial charge, accumulators, 470
Input—
  impedance, transformer, 202
  losses, transformer, 200
Instability, 335, 343
Installation, television receiver, 582
Instruments—
  electrodynamic, 113
  electromagnetic, 108
  electrostatic, 119
  indicating, 102
  recording, 102
Insulators, 18
Inter-electrode capacity, 335
  valve, 351
Interference—
  beat, 376
  filters, 485
  inverter, 573
  motor ignition, 582, 589
  second channel, 361, 365
  suppression, 456
  types of, 457
Interlaced scanning, 556
Intermediate frequency—
  amplifier, 285, 571
  stages, 360, 481
  stages, television receiver, 571
Inverter—
  control, 587
  interference, 573
Ionic—
  drift, 19
  heated cathode valve, 324
Ionization, 134, 323
  gases, in, 15
Ionosphere, 617
Ions, 19, 99, 134
Iron—
  cored transformer, 392
  eureka thermocouples, 49
  magnetic properties of, 181

Kilocycles, 124
Klystron, reflex, 676

Lamps—
  arc, 64
  discharge, 65
  fluorescent, 66
  gas filled, 64
Lattice chart, 611
Law—
  Ohm's, 147, 159, 234, 264, 311
  square, 105
  Steinmetz's, 237
Layer, Heaviside, 134, 377, 600
Leads, microphone, 430
Lead-acid cells, 463
Leaky grid—
  detector, 301, 306
  rectification, 348
Leclanché cell, 37
Lee de Forest, 257
Left hand rule, Flemings, 70, 85, 668
Lighting, electric, 64
Limiter, 140
Limiting frequency triodes, 643
Line—
  artificial, 646
  scan, 493, 554
  time bases, 577
  transmission, 499, 649
Linear scales, 104, 112
Linearity, 563
  control, 587
Liquid(s)—
  conduction in, 20
  damping, 104
Lissajous, 521
Lithium, 537
Litz wire, 254
Load—
  anode, 266, 332
  resistance, 332
  optimum, 398
Local oscillator, 353
Log law (log line) condenser, 217
Logarithmic graph, 128
Long-range warning sets, 619, 633
Loop—
  aerials, 592
  hysteresis, 184
  outboard, 602
  retractable, 603
  system, rotatable, 602
Loran, 609
Losses, eddy current, 392
Loudspeakers, 411
  beam distribution, 419
  dual, 420
  horn, 411
  inductor type, 413
  magnetic system, 414
  matching, 194, 415
  moving coil, 413
  permanent magnet, 414
  phasing, 423
  transformer ratios, 416
  volume control, 422
Low frequency—
  amplification, 385, 484
  chokes, 189, 241
  coupling units, 209
  oscillation, transformer, 214
  stage, 482
Lumen, 538

Magic-eye indicators, 373
Magnetic—
  deflection, 573
  effects of currents, 66
  field, solenoid, 68
  focusing, 529, 575
  pick up, 431
  properties, iron, 181
  system, loudspeaker, 414
Magnetism, residual, 183
Magnetizing force, 182
Magneto striction pick-up, 434
Magnetron, 644
  multi-resonator, 672
  R F generators, 651
  resonant, 667
  split anode, 669
Magnification factor, 253
Mains—
  lead chokes, 178
  supply, 439
  transformers, 448
  triode heptode, 285
Manganin, 107
Map, polar, 665
Marconi, 132
Marconi-Reiss microphone, 425
Matching—
  feeders, 510
  loudspeaker, 184, 415
  transformers, 512
Maxwell, Clark, 27, 130
Mazda, electrode assembly of—
  mains R.F. pentode, 276
  TH41, 285
  triode, 263
Measurement—
  bearing, 626
  range, 665
  target height, 616
Mechanical analogy, cathode-ray tube, 26
Medium wave stopper, 177

Mercury vapour—
  discharge lamp, 65
  rectifier, 322
  relay, 524
Metal rectifiers, 111, 447
Metallized resistances, 166
Meters—
  hot wire, 118
  induction, 115
  induction, watt-hour, 116
  moving coil, 110
  moving iron, 108
  rectifiers, 97
  scales, 104
  supply, 108
  thermocouple, 118
  type indicator, 604
Mho, 266
Mica, 223
Micro-dial, 226
Microfarads, 242
Microhenry, 231
Micromho, 266
Microphones, 137, 424
  carbon, 424
  condenser, 140, 246
  crystal, 247
  leads, 430
  Marconi-Reiss, 425
  moving coil, 247
  ribbon-type, 429
  Rothermel-Brush, 428
  transverse current, 425
  velocity, 429
Miller effect, 270
Milliammeters, 120, 372
Millihenry, 231
Miniature C.R. tubes, 532
Minimum impedance, 247
Mis-match, 511
Mistuning, 371
Mixer—
  pentagrid, 293
  valve, 364
Mixing, 482
Modes, 654, 674
Modulation, 341, 497
  amplitude, 137
  C.R. tube, 576
  cross, 273, 285, 289
  frequency, 138
Molecular strain, 29
Molecules, 12
Morse code, 135, 497
Motor(s)—
  A.C. 79,
  A.C. commutator, 89
  auto-synchronous, 89
  car interference, 582, 589
  car radio, 484
  compound, 73, 77
  D.C., 70
  generators, 456
  induction, 80
  pony, 89
  principle, 69
  series, 73, 76
  shaded pole, 87
  shunt, 73
Motor(s)—*contd.*
  squirrel-cage, 89
  synchronous, 88
  two-phase, 86
Motor-driven tuning devices, 376
Moving coil—
  loudspeaker, 413
  meters, 110
  microphone, 247
Moving iron meters, 108
Mullard, FC3A valve, 291
Multi—
  assembly output valves, 320
  beam speaker assembly, 421
  range moving coil meters, 112
  resonator magnetron, 672
Multiplier, electron, 55, 542
Mumetal, 189
Mutual—
  conductance, 265
  induction, 199, 202, 231, 234

Negative—
  feedback, 303, 310, 316, 406, 571
  resistance, tetrode, 272
Neon discharge—
  lamp, 523
  tube indicators, 604
  tubes, 373
Networks, smoothing, 443
Neutrodyne circuits, 335
Neutrons, 13
Nickel-iron cell, 468
Node, 507
Noise—
  background, 371
  suppression, 384
Non-linear scale, 104
Nucleus—
  copper, 14
  helium, 14
Number, atomic, 14

Oersted, 101
Ohm, Professor, 237
Ohm's Law, 147, 159, 234, 264, 311
Open aerial, 597
Optimum—
  load, 398
  viewing distance, 585
Oscillator—
  drift, 370
  feedback, 364
  frequency, 51
  grid, 288
  Hartley type, 644
  local, 353
  self-pulsing, 648
  stage, 285
  Wein bridge, 639
Outboard loops, 602
Output—
  power, 399
  stage, 396
  valve, pentode, 313
  valves, multi-assembly, 320

Parabolic reflector, 505, 634
Parallel—
  circuit, resonance, 252
  connections, resistances 158
  feed, 172, 208
  feed auto-transformer, 395
  feed transformer coupling, 394
  feedback, 319
  wire feeders, 499
Pattern(s)—
  anode voltage, 675
  radiation, 627
Peak power, 640
Pentagrid, 291, 364
  mixer, 293
Pentode bias resistance, 173
Pentode valve, 275, 310, 352
  double diode, 344
  output 313
Permalloy, 185
Permanent magnet loud speaker, 414
Permeability, 182, 185
Permittivity, 29, 31
Phantom anode, 292
Phasing loudspeakers, 423
Photo—
  conductivity, 535, 543
  electric emission, 22, 35, 53, 535
  electric materials, 535
Photocells, 535, *et seq.*
  emission type, 54, 539
  gas-filled, 539
  rectifier type, 546
  vacuum, 539
  valve amplification, 541
Photovoltaic effect, 535, 545
Pick-up, 168, 431
  crystal, 432
  magnetic, 431
  magneto- striction, 434
  screening, 436
  volume control, 172, 435
Picture hold control, 586
Piezo-electric crystals, 51, 420, 427, 432
Piezo-electricity, 51
Piston, tuning, 652
Plate(s)—
  beam-forming, 314
  deflector, 519
  Faure, 464
  Planté, 464
Pneumatic damping, 104
Polar—
  diagram, 502
  diagram, loop aerial, 594
  map, 665

Polarization, 37
  current, 28
Pony motor, 89
Portable superhet. receiver, 480
Position finding, 607
Positive—
  feedback, 316, 343, 479
Potassium, 537
Potential—
  contact, 261
  difference, 16
  divider, 165
Potentiometers, 147, 167, 212
Powders, fluorescent, 66
Power, 66, 199, 640
  factor, 200
  factor compensator, 117
  frequencies, 123, 236
  grid detection, 303, 351
  output, 399
  output tetrode, 313
  pack, E.H.T., 580
  peak, 640
  rating, resistance, 157
  supply, 437
  supply, C.R. tube, 532
  supply, television receiver, 494
  unit, 164
P.P.I. display, 664
Predetector volume control, 170
  emphasis, 410
  set resistances, 165
Primary—
  cells, 36
  electrons, 24
  tappings, mains transformers, 448
Probe waveguide, 654
Propagation of radio waves, 130
Protons, 13
Public address equipment, 403, 411, 421
Puckle hard valve time base, 526
Pulling, 371
Pulse-modulated systems, 609
Pulse(s), 647
  control, 651
  repetition frequency, 640
  synchronizing, 558, 565
  trigger, 647
  width, 640
Pulsing systems, classification, 644
Push-button systems, 375
Push-pull—
  amplification, 141, 401
  analogy, 402
  Class A, 400
  Class AB, 406
  Class B, 320, 404
  quiescent, 320, 405
Push-Pull—*contd.*
  R.F. generator, 648
  transformers, 212
Pythagorus' theorem, 239, 243

" Q " for oscillatory circuits, 649
Quadrature errors, 603
Quadrupler, voltage, 322
Quarter-wave radiator, 508
Quenching, 308
Quiescent push-pull, 320, 405
Quiet A.V.C., 384

Radar, 296, 326, 615 *et seq.*
  airborne sets, 619
  beacon stations, 620
  receivers, 660
  system, basic, 634
  system, constants, 639
  transmitters, 643, 648
Radiation—
  diagrams, 502
  electromagnetic waves, 591
  pattern, 627
  resistance, 501
Radiator—
  quarter-wave, 508
  unipole, 508
Radio—
  compasses, 603
  detection, 615
  direction finding, 591 *et seq.*
  frequencies, 123
  -goniometer, 598
  -telephony, 136
  waves, 123, 130
Radio-frequency—
  amplification, 276, 329, 366
  amplifier, triode as, 269
  carrier, 341
  circuits, 333
  valve 329
  valve stages, 340
Radiolocation, 591
Radiometal, 189
Range measurement, 665
Ranging, 615
Raster, 556
Ray, direct, 134
Reactance, 238
Reaction, 306, 343
Receiver(s)—
  A.C., 439
  A.C./D.C., 450
  car, 484
  circuits explained, 477 *et seq.*
  F.M. system, 140
  portable superhet, 480
  radar, 660
Receiver(s)—*contd.*
  short-wave, 353
  straight three valve, 478
  superheterodyne, 333, 353, 480 *et seq.*
  television, 553
Reception, short wave, 371, 509
Reciprocity theorem, 509
Recording, 409
  instruments, 102
Recovery time, 637
Rectification, 262, 296, 483
  full-wave, 97
  half-wave, 96
  leaky grid, 348
Rectifier(s), 96
  cold-cathode, 324
  diode, 141
  full-wave, 441
  half-wave, 439
  ionic-heated cathode, 324
  mercury vapour, 322
  metal, 97, 111, 447
  moving coil meter, 111
  photocells, 546
  valve, 98, 320, 443
Rediffusion systems, 144
Reflection of waves, 133
Reflector, 143, 504
  dipoles, 583
  parabolic, 505, 634
Reflex klystron, 676
Regeneration, 307
Relay—
  electromagnetic, 69
  gas-filled, 524
  mercury vapour, 524
  systems, broadcast, 144
Remanence, 185
Reservoir analogy, 17
Residual magnetism, 183
Resistance(s), 147, *et seq.*
  A.C., calculating, 237
  anode, 160
  bias, 290
  capacity coupling, 389
  cartridge type, 166
  centre-tapped, 174
  choke H.F., 176
  coupled stages, 387
  D.C. mains, 164
  decoupling, 165, 172
  dynamic, 202, 277
  effective, 237
  feed system, 210
  grid bias, 162
  grid leak, 160, 171, 390
  load, 332
  metallized, 166
  parallel connections, 158
  pentode bias, 173
  power rating, 157
  pre-set, 165
  radiation, 501
  series connection, 157
  series-parallel connection, 158
  shunt, 106
  spaghetti, 163

Resistance(s)—*contd*
sparking plug, 166
"stopper," 172
tapped anode, 161
temperature coefficient, 58
variable, 162
welding, 59
wire-wound, 163
Resistor, bleeder, 324
Resonance, 250, 393
Resonant—
cavity, 657 673
frequency, 249
magnetron, 667, 671
wire, 505
Response—
curves, H F., 337
frequency, 394
spectral, 538
Retractable loops, 603
Ribbon-type microphones, 429
Right hand rule, Fleming's, 40, 74, 84
Rotary—
beacons, 605
spark gap, 652
transformers, 455
Rotatable loop system, 602
Rotating field, 80, 83
Rochelle salt, 51, 420, 432
Rontgen Society, 552
Rothermel-Brush micro-phone, 428
Rotor, 80, 83
Rubidium, 537
Rutherford, 9, 31

Salt, Rochelle, 51, 420, 432
Saturation, 188
Savart, 101
Saw-tooth wave-form, 522
Scan—
frame, 493, 554
generators, 555
line, 493, 554
Scanning, 554
interlaced, 556
Scratch filters, 435
Screen
calibration, 621
fluorescent, 26, 520
Screened twin feeders, 499
Screening—
canister, 368
grid supply, 171
pick-ups, 436
Seam welding, 60
Second channel interference, 361, 365
Secondary cell, 463
emission, 25, 35, 54, 275, 314, 542
load transformer, 394
Selectivity, 359, 497
channel, 359
H.F. stage, 336
Selenium, 543
bridges, 544
-iron cell, 547
Self—
induction, 231
pulsed R F. generators, 644
pulsing oscillator, 648
rectifying vibrator, 455
Sense determination, 595
Sensitivity, human ear, 206
Separately-excited dynamo, 48
Separation—
frequency, 138, 342, 359
synchronism, 566
Separators, 463
Series—
booster, connections, 93
connection of resistances, 157
motor, 73, 76
parallel connections of resistances, 158
Servicing accumulators, 473
Shaded pole motor, 87
Short wave(s), 131, 495
chokes, 178
receivers, 353
reception, 371, 509
superheterodyne, 179
transmission, 498
Shunt—
motor, 73
resistances, 106
-wound dynamo, 48
Sidebands, 138, 368
Single phase—
alternator, 44
induction motor, 86
Skin effect, 236
induction motor, 85
rotor, 80
Smoothing—
chokes, 195
networks, 443
"Smeller," 618
Sodium, 537
Solenoid, 79
magnetic field, 68
Sound waves, 136
Spaghetti, resistances, 163
Spark—
gap, 657
transmitters, 135
Sparking plug resistances, 166
Speakers—
extension, 422
multibeam, 421
Specific inductive capacity, 221
Spectral response, 538
Speech coil, 414
Speed control—
compound motor, 77
series motor, 77
shunt motor, 75
Speed of rotating field, 83
Split—
anode magnetron, 669
end-plate condensers, 2
Splitting—
atom, the, 9
beam, 632
Spot welding, 60
Square law, 105
condenser, 216
scales, 113
Squirrel cage motors—
rotor, 80
starting, 90
winding, 89
Stacked dipoles, 634
Stage—
frequency changer, 285
gain, 277, 281
oscillator, 285
Stalloy, 198
Starter, automatic, 78
Starting—
A.C. motors, 91
D.C. motors, 78
single-phase induction motor, 87
squirrel-cage motors, 90
Static field, 229
Stator, 80
Steinmetz's law, 237
Stopper—
medium wave, 177
resistance, 172
Straight line—
capacity condenser, 216, 227
frequency condenser, 217
Straight three valve re-ceiver, 478
Strain—
dielectric, 29
molecular, 29
Stratosphere, 134
Stray capacities, trans-former, 393
Strontium, 537
Stubs, use of, 513
Subsidiary hysteresis loop, 187
Superheterodyne, 285
receivers, 333, 353, 480, *et seq.*
short-wave, 179
Super-regeneration, 307
Supersonic frequencies, 358
Supply—
mains, 439
meters, 108
power, 437
Suppression—
high or low notes, 211
interference, 456
noise, 384
Suppressors, 459
grid, 275
Swing bearings, 593
Swinton, Campbell, 517, 552
Switch, T.R., 655

Switching—
beam, 658
controls, 376
symmetrical deflection, 527
synchronism separation, 566
synchronization, television, 562
Synchronizing pulses, 558, 565
Synchronous motor, 88

Tapped—
anode resistance, 161
output chokes, 193
Target, 373
height measurement, 616
Television, 551, *et seq.*
beacons, 607
synchronization, 562
time base, 559
transmitter, 552
transmitting aerial, 508
Television receiver, 553
aerial, 583
circuit diagram, 569, 574
detector stage, 572
frequency changer, 570
I.F. stages, 571
installation, 582
maintenance, 588
power, pack, 580
power supply, 494
superheterodyne, 489
Temperature coefficient, resistance, 58
Testmeter, AvoMinor D.C., 112
Tetrode valve, 271
power output, 313
Thermal type meters, 118
Thermocouple(s), 50, 111
chromel-alumel, 49
copper-eureka, 49
iron-eureka, 49
meters, 118
Thermo-electric effects, 49
Thermionic emission, 22, 35, 52, 258
Threshold wavelength, 537
Thyratron, 324
Time base(s), 493
calibration, 623
circuits, 521
frame, 579
frequency, 525
generator, 621
line, 577
Puckle hard valve, 526
television, 559
voltage, 625
Time, recovery, 637
Tone—
control chokes, 194
control transformers, 210
correction, 173
difference, 355
Tracking arm, 436
Transconductance, 266
Transformer(s), 94, 199
air cored, 332
amplitude distortion, 205
audio-frequency, 204
calculation, 203
centre-tapped, 402
coupling, 392
E.H.T., 582
frequency distortion, 204
H.F., 338
impedance, 202, 512
input losses, 200
iron cored, 392
L.F. oscillation, 214
mains, 448
matching, 512
performance curves, 208
push-pull, 212
ratios, loudspeakers, 416
rotary, 455
secondary load, 394
stray capacities in, 393
tone control, 210
tuned, 292
turns ratio, 201
Transmission—
C.W., 135
lines, 499, 649
short waves, 498
Transmitter(s)—
Alexandra Palace, 565
Hertz, 131
lay-out, 137
radar, 643, 648
spark, 135
television, 552
Transmitting—
aerial, television, 508
receiving switch, 655
valves, 325
Transverse current microphone, 425
Trigger pulses, 647
Trimmers, 225, 340
Triode valve(s), 263
amplifier, as, 267
double diode, 344
gas-discharge, 324
heptode, mains, 285
hexode, 285, 364
limiting frequency, 643
pentode, 293, 364
section frequency changer, 290
Tube—
cathode-ray, 25, 517 *et seq.*, 553, 604, 620
gas, 23
neon, discharge, 373
vacuum, 21
Tuned—
anode, 278, 479
circuits, 234, 245, 332, 359
grid coupling, 280
transformer, 282
Tuneon indicator, 373
Tuneray indicator, 448
Tungsten, 258
Tuning, 229
band-pass, 211, 338
coils, 256, 336
condenser vanes, 216
devices, automatic, 374
indicators, 372
motor-driven devices, 376
piston, 652
Turns ratio, transformer, 201
Tweeter, 420
Twin feeder, 583
Two-phase motors, 86

Ultra short waves, 131, 495
Unipole radiator, 508
Unit(s)—
display, 663
power, 164

Vacuum—
conduction in, 21
photocells, 539
tubes, 21
Valve(s), 257 *et seq.*
American, 291
amplification, 388
amplification, photocells, 541
audio-frequency amplifier, 310
beam tetrode, 314
cathodes, 58
Cossor, 41MTL, 264
Cossor 41 M.T.S., 566
Cossor 42 O.T.D.D., 320
Cossor MSG/LA, 272
Cossor PT41B, 316
diode, 257, 259
double diode, 344
frequency changer, 284
H.F. stages, 384
impedance, 336
interelectrode capacitance, 351
Mazda R.F. pentode, 276
Mazda TH41, 285
Mazda triode, 263
mixer, 364
Mullard, FC3A, 291
multi-assembly, output, 320
pentagrid, 291
pentode, 275, 352
radio-frequency stages, 340
rectifiers, 98, 320, 443
tetrode, 271
transmitting, 325
triode, 263
triode, gas-discharge, 324
triode hexode, 285, 364
triode pentode, 293, 364
variable-mu, 378
velocity modulated, 676
water-cooled, 326

Vanes, tuning condenser, 216
Variable—
automatic grid bias, 171
condensers, 223
-mu valve, 284, 378
resistances, 162
Vector—
impedance, 243
representation, 243
Velocity—
microphones, 429
modulated valve, 676
wireless waves, of, 126, 496
Vernier drive, 226
Vertical radiation pattern, 628
Vibrator(s), 454
circuit, 485
Video—
circuits, 573
detector, 568
Viewing distance, optimum, 585
Vision—
channel, 557
persistence of, 551
Visual indicators, 603
Voltage—
doubler, 322
drop calculations, 156
dropping, 164
multiphase systems, 81
node, 507
quadrupler, 322
Voltage—*contd.*
ripple, 47
single phase system, 81
time base, 625
Voltmeters, 106, 113, 115, 119
Volume—
compression, 408
expansion, 409
Volume control—
automatic, 308, 377
loudspeakers, 422
pick-up, 172, 435
pre-detector, 170

Wander plugs, colour code, 439
Water-cooled valves, 326
Watt-hour, induction, meters, 116
Wattmeters, 107, 114, 116
Wave(s)—
analogy, 136
carrier, 136
electromagnetic radiation, 591
radio, 123
reflection of, 133
short, 131
sound, 136
ultra short, 131
velocity of, 126, 496
Wave-form, saw-tooth, 522
Waveguide(s), 653
feeder systems, 654
Wavelength(s), 125, 250, 495
frequency chart, and, 155
frequency, conversion, 126
threshold, 537
Wehnelt cylinder, 518, 529
Weight, atomic, 14
Wein bridge oscillator, 639
Welding—
arc, 61
butt, 60
resistance, 59
seam, 60
spot, 60
Widths—
beam, 630
pulse, 640
Winding, squirrel-cage motor, 89
Wire—
Litz, 254
resonant, 505
-wound resistances, 163
Wireless—
circuits, induction, 233
waves, velocity of, 126

"X" plates, 519, 622, 664
X-rays, 517

"Y" plates, 519, 622, 664